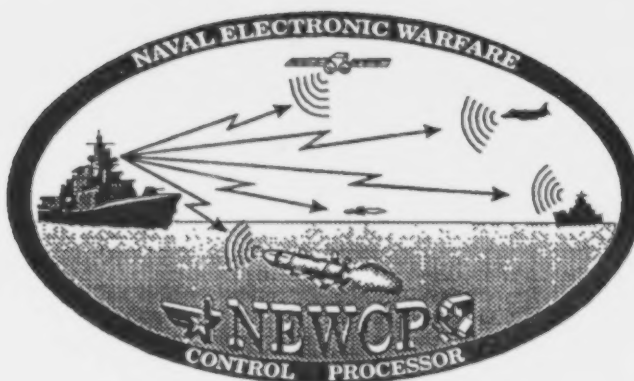




*The Integration Of
Electronic Warfare Assets On
Maritime Platforms
PHASE I*

**EFFECTIVENESS
OF
COUNTERMEASURES**

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THE INTEGRATION OF ELECTRONIC WARFARE ASSETS
ON MARITIME PLATFORMS
PHASE 1

EFFECTIVENESS OF COUNTERMEASURES

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1. Introduction

This document is submitted by Lockheed Canada and Thomson Systems Canada in partial fulfillment of the requirements of Phase I of the "Integration of Electronic Warfare Assets on Maritime Platforms" project (DSS Contract W7714-2-9616/01/ST). This report is a working paper that documents the results of the activities identified under the "Effectiveness of Countermeasures" (task 2200) as described in the proposal submitted to DREO.

This document is divided into 9 chapters. The purpose of each of these chapters is briefly outlined below:

Chapter 1: Introduction;

Chapter 2: Description of the approach taken to the elaboration of effectiveness assessment function. Central to this material is the distinction between high level effectiveness assessment and low level effectiveness assessment;

Chapter 3: Description of low level effectiveness assessment functionality. The emphasis is upon the comparison of specific threat behaviours to expected behaviours. Effectiveness assessment techniques addressed in this chapter include the measurement of radar mode changes, the measurement of missile trajectory deviations, the detection of threat seeker jogs, and the measurement of chaff reflections.

Chapter 4: Description of high level effectiveness assessment functionality related to the use of ECM to prosecute search / targeting radars. Emphasis is placed upon the capability of CPF sensors to provide effectiveness assessment support in this context;

Chapter 5: Description of high level effectiveness assessment functionality related to the use of ECM to threat seeker radars. Emphasis is placed upon the capability of CPF sensors to provide effectiveness assessment support in this context;

Chapter 6: Analysis and expansion of AMEP concepts for possible use within the context of the NEWCP;

Chapter 7: General description of the applicability of AI software technologies and uncertainty management systems to the NEWCP problem domain;

Chapter 8: Identification and description of equipment, facilities, software tools, and simulation software that might be used to validate algorithms for ECM effectiveness assessment;

Chapter 9: Conclusion

2. ECM Effectiveness Assessment

The purpose of this section of the report is to describe a framework for the presentation of ECM effectiveness assessment concepts and functions.

The comparison of measurements to associated predictions is central to the effectiveness assessment problem domain. As will be seen in the remainder of this section, effectiveness assessment is best described in terms of a number of hierarchical levels. For each such level, effectiveness assessment is performed by measuring combat environment parameters and comparing these measurement to a template of expected, or predicted values.

2.1 Multiple Level Model of Effectiveness Assessment

Of central importance to our presentation of ECM effectiveness assessment functionality is the notion that effectiveness assessment has different meanings at different levels of problem domain description. For example, the following two ECM effectiveness assessment requirements are both meaningful but each is associated with a different level of problem domain description:

1. Determine whether the deployment of distraction chaff at location (x,y,z) and time (t) has ensured that missile 2 (at range R, azimuth A, with velocity V) will not intercept ownship;
2. Determine whether RF reflections coming from the chaff cloud are consistent with the hypothesis that missile 2 is tracking the chaff cloud (and not the ship).

Clearly item 1 is a requirement that describes the problem domain at a higher level of description than requirement 2. The fact that requirement 2 can be satisfied without requirement 1 being satisfied is an indication that low level effectiveness assessments (such as statement 2) may not be sufficient for the determination of the outcome of an engagement.

The effectiveness assessment problem domain is most appropriately characterized in terms of a hierarchy of requirements. It is proposed that effectiveness assessment functionality be elaborated in terms of four levels:

- ECM level
- EW Tactical level
- EW Engagement level
- EW Battle level

The proposed approach provides a mechanism for addressing the following four questions, which collectively serve to define the requirements for EW effectiveness assessment:

1. Has the deployment of a specific EW countermeasure been successful in eliciting specific

responses from the threat? [ECM Level];

2. Have fundamental identifiable tactical objectives (e.g. avoidance, seduction) been achieved with respect to the prosecution of a particular threat? [EW Tactical Level];
3. Has the overall strategy applied to engaging a particular threat succeeded in ensuring that the threat will not intercept ownship? [EW Engagement Level];
4. In an environment characterized by multiple threats, has the overall EW battle strategy been such as to minimize the overall risk of damage to ownship? [EW Battle Level].

Each of the above questions defines effectiveness assessment requirements at increasingly higher levels of problem domain description. As a general principle, it should be stated that effectiveness assessment at any particular level will incorporate the outcomes of effectiveness assessments at the level immediately beneath it.

Finally it is beneficial to clarify the respective roles of the CCS and the NEWCP with regard to effectiveness assessment. The NEWCP, with its specialized embedded knowledge of EW, is responsible for generating an assessment concerning the outcome of the battle from a strictly EW perspective. Evaluations at each of the four levels identified above contribute to such an assessment. However, the CCS retains executive authority concerning how such information is used with respect to ship defence activities in general. The CCS has the most comprehensive tactical picture and is responsible for a final determination of whether the threat has been defeated or not.

The following material provides an overview of effectiveness assessment functionality at each of the four levels identified above.

ECM Level

ECM level effectiveness assessment occurs within the context of the engagement of a single threat by a single EW asset and involves the measurement of threat behaviours / parameters and the comparison of such measurements to expected values. The following are phenomena whose measurement and subsequent comparison to an expected value are representative of effectiveness assessment at the ECM level:

- Chaff reflections;
- Threat radar jog;
- Threat radar mode transition;
- IR profile changes;
- Doppler shifts in threat's emitted radar signal;
- Threat trajectory change;

- etc.

Such measurements represent attempts to measure or characterize threat responses to particular ECM deployments such as chaff, X-pol, etc. Once a measurement has been made, it is necessary that it be compared to an associated predicted value. The nature of this comparison is such that relevant attributes of the threat - countermeasure system are duly accounted for. Consider the following representative example:

Chaff reflection measurements will be initiated only after that time at which the specific threat under prosecution could reasonably be expected to have been decoyed by the chaff. The direction from which chaff reflections are to be expected will be based upon the geometry of the [threat - chaff] system. Furthermore, the characteristics of the measured reflections (e.g. frequency, PRF, etc.) will be compared to the known emissions characteristics of the threat under prosecution.

As this example illustrates, effectiveness assessment, even at the lowest of all levels, requires that use be made of tactical situation information such as timelines, engagement geometry, threat and countermeasure attributes, etc.

Tactical Level

Effectiveness assessment at the tactical level involves the activity of determining whether specific tactical objectives have been achieved with respect to the prosecution of a particular threat. Possible tactical objectives include avoidance, dilution, confusion, and seduction. A particular threat-specific tactical objective can be achieved through the use of a single EW asset (e.g. confusion chaff) or as a result of the combined use of countermeasures (e.g. RGPO and chaff).

Tactical level effectiveness assessment consists of a determination of whether tactical objectives have been achieved. Consider, for example, the use of seduction chaff. The tactical objective is to cause the threat to transfer lock onto the chaff cloud and pursue it as its target. The achievement of this tactical objective is determined by integrating ECM level effectiveness assessments that provide information about threat trajectory changes. Such lower level ECM effectiveness assessments may involve doppler shift measurements and chaff cloud measurements as well as more direct measurements of threat trajectory.

All these lower level assessments are integrated together to support a determination of whether the tactical objective has been accomplished - in this case the introduction of trajectory changes consistent with a seduction tactic.

Engagement Level

Effectiveness assessment at the Engagement level involves the determination that the overall EW strategy applied in order to defeat a specific threat has been successful. In this respect, it is important to note that the NEWCP employs a layered EW defence strategy in the prosecution of individual threats. More specifically, as the attack sequence unfolds, different tactical responses, specifically avoidance, distraction, confusion, and seduction are appropriate in order to defeat the threat. The conditions under which an avoidance response is suitable occur early in the engagement whereas the conditions under which a seduction response is suitable occur late in the engagement.

This layered defence strategy is employed in order to increase the likelihood that the threat will ultimately be defeated by EW. The threat is considered to have been defeated if it is concluded that it will not cause damage to ownship.

Whereas effectiveness assessment at the tactical level involves determining whether specific tactical measures undertaken (e.g. avoidance, seduction) have been successful, engagement level effectiveness assessment involves determining whether the combined effect of such measures has been such as to ensure that threat will not intercept ownship. The evaluation is ultimately forwarded to the CCS.

Effectiveness assessment at the engagement level will include, for example, such activities as determining whether the threat is capable of intercepting ownship given known (or posited) threat field-of-view and lateral acceleration characteristics. Furthermore, engagement level effectiveness assessment may involve the integration of effectiveness assessment outcomes from the tactical level in order to assess the likelihood that the threat has been defeated.

Battle Level

Effectiveness assessment at the battle levels deals with a determination of whether EW actions undertaken are optimal with respect to ship survival in a combat environment that will generally be characterized by multiple threats. Battle level effectiveness assessment is not threat-specific but rather serves to characterize the overall effectiveness of EW activities in ensuring that ownship will survive the threat posed by a multi-threat attack. As such, battle level effectiveness assessment will be based upon integrating threat-specific effectiveness assessments each weighted in some manner that reflects the degree of menace posed by the threat in question.

By way of example, assume the existence of a particularly dangerous threat A as well as a less dangerous threat B. Effectiveness assessment at the engagement

level will indicate whether or not these individual engagements have been successful. However, a higher level assessment should still be made - for example if only one threat can be defeated it is better if this threat = A. The assessment of whether the complete program of EW activity has succeeded in optimizing ship survival takes place at the battle level where due account is taken of all threats in the combat environment.

Effectiveness assessment at the battle level addresses the possibility that EW actions undertaken may place ownship at risk. By way of example, consider that the actions of Engagement Manager A associated with threat 1, might somehow beacon threat 2, associated with Engagement Manager B, onto ownship. Recall that Engagement Manager B is, by definition, not even aware that threat 1 exists or that EW actions have been undertaken against it. Accordingly, Engagement Manager B may not be capable of making sense of the fact that threat 2 is being beacons onto ownship. Higher level (i.e. battle level) effectiveness assessment functionality is required to resolve such a situation.

A related phenomena involves the possibility of fratricide - that the actions of an Engagement Manager associated with ship A might beacon a threat onto ship B. Suppose that ship B is successfully engaging two threats. Effectiveness assessment at the engagement level (for ship B) might indicate that each threat is defeated. Higher level assessment functionality is required to account for the presence of the third, "beaconed" threat. Such functionality is most appropriate at the battle level, where a complete characterization of the combat environment is available.

A third phenomena with effectiveness assessment implications at the battle level relates to the issue of interference. Consider a situation where Engagement Manager A is prosecuting threat 1 with a jammer while Engagement Manager B is using chaff to prosecute threat 2. It is possible that the chaff cloud will obscure the line of sight from the jammer to threat 1. This may well disrupt the effectiveness assessment activities of engagement manager A as well as tactical level and ECM level effectiveness assessment activities related to the engagement of threat 1. It is only at the battle level of description that an interaction of this type can be properly accounted for.

Strictly for the purposes of brevity, the remainder of the material in this chapter describes ECM effectiveness assessment functionality at two levels. Roughly speaking the lower of these two levels encompasses the functions and activities associated with the ECM and EW Tactical levels as described above. Similarly, the higher of these two levels corresponds to the EW Engagement and EW Battle levels of effectiveness assessment.

The higher level of effectiveness assessment description involves a context dependant

characterisation of effectiveness assessment in relation to the overall tactical objective associated with the ECM deployment as well as the overall tactical situation. By comparison, the lower level of effectiveness assessment description involves the determination of whether specific threat behaviours have been influenced by ECM (e.g. has X-pol induced a jog?, has noise jamming induced a radar state transition?, etc.). High level ECM effectiveness assessment functionality is addressed in chapters 4 and 5 of this report.

2.2 Low Level Effectiveness Assessment

Lower level effectiveness assessment, in the way we will use the term, comprises the techniques and methods traditionally associated with softkill effectiveness assessment. These include the measurements of jogs, radar state transitions, trajectory deviations, and chaff reflections. These techniques will be elaborated upon in section 3 of this report.

A more detailed specification of the topics to be addressed in chapter 3 is provided in the following list:

- Detection of radar mode changes;
- Direct measurement of missile trajectory changes;
- Detection of jog conditions;
- Measurement of reflections from chaff;
- Detection of cross-polarization deviations;
- Measurement of doppler shifts associated with received seeker emissions;
- Detection of changes to threat IR signature;
- Direct measurement (via high resolution radar) of apparent changes in missile length along radial (inbound) axis.

These low level effectiveness assessment techniques will be described, in large measure, in a manner that is independent of context. The approach selected is to address context-dependencies at the higher level. As the examples in section 2.6 indicate, this division of effectiveness assessment functionality into levels is not entirely natural - there may well be context dependencies at the lower level. Nevertheless, it is considered that an attempt to deal with all context dependencies at the lower level would result in unmanageable complexity of presentation.

2.3 High Level Effectiveness Assessment

A major conclusion of the work done thus far on ECM effectiveness assessment is that lower level techniques must be used in a coordinated manner within a wider context in order to fully determine whether an ECM deployment has been successful. We will now address the issue of high level effectiveness assessment in more detail.

Effectiveness assessment does not mean simply measuring some physical phenomena and comparing this measurement to some expectation that is relatively independent of the details of the deployment and the state of the overall combat environment. There will (almost) always be a higher level context that must be accounted for. There are many elements that comprise this context including tactical objectives, threat states, ship states, environmental conditions, etc.

A higher level description of effectiveness assessment is required for a variety of reasons. First, effectiveness assessment appears to be highly context-specific. It does not appear that it is possible to define strictly generic softkill effectiveness assessment techniques (i.e. methods for determining softkill effectiveness without considering the specifics of the current tactical situation). The first illustrative engagement example, in section 2.6, demonstrates this: how one uses chaff reflections to perform effectiveness assessment is dependant upon the details of the deployment - in this example whether chaff has been deployed for distraction or seduction purposes.

It is important to underscore that such context dependencies reflect a need for fundamental differences in effectiveness assessment functionality for different tactical situations, not merely differences in timelines, thresholds, etc. Another example of effectiveness assessment context dependency involves the temporal correlation of engagement events. For instance, consider the observation that a threat seeker has transitioned from search mode to acquisition mode. If this transition occurs shortly after an active decoy has even been activated, it may provide evidence to support the hypothesis that the threat has acquired the decoy. Conversely, if the same transition occurs at a different time, say before the decoy has been activated, the observation obviously provides little or no support to the hypothesis that the seeker has acquired the active decoy.

Another reason for considering effectiveness assessment at a higher level involves the notion that information from a variety of specific, lower level, effectiveness assessment techniques, needs to be integrated together in order to determine engagement outcome. For some engagement situations, no individual lower level effectiveness assessment technique (e.g. jog detection) will be sufficient, in and of itself, to determine whether the threat has been defeated. In fact, one can imagine a situation in which individual low level effectiveness assessment techniques each provide weak support for a conclusion of success yet, considered collectively, provide strong support for a conclusion of engagement success. In this light, softkill effectiveness assessment can be viewed, at least in part, as a high level process whereby evidence from a variety of sources is combined in order to determine engagement outcome.

The issues discussed in the preceding paragraph serve to illustrate, to some degree, the manner in which the two levels of effectiveness assessment interact. Lower level effectiveness assessment consists of a fairly broad range of techniques, each of which provides information descriptive of one aspect of the effectiveness assessment problem. These separate pieces of information (e.g. radar indicates threat trajectory change, ESM indicates change in threat radar state, ESM indicates doppler shift in threat RF emissions) are integrated and interpreted at a higher level where due consideration is given to the overall tactical objective as well as to other elements and characteristics of the combat environment.

As will be discussed in section 7 of this report, the requirement to integrate uncertain information (or perhaps more appropriately, evidence) from a variety of sources gives rise to a related requirement for a method(s) to characterize the confidence with which any final softkill effectiveness determination is held. There are a variety of approaches to the integration of uncertain information (known as Uncertainty Management Systems) and these will be addressed in section 7.

Another aspect of a high level description of softkill effectiveness assessment relates to unanticipated effects of ECM decoys that, while present in the environment, may no longer be part of a specific NEWCP tactic. Consider, for example, a rubber duck that is still present in the general vicinity of the ship even though the NEWCP action it was involved in has come to an end. Such a decoy may conceivably still affect the behaviour of threats in the combat environment. Such effects could conceivably be favourable or deleterious. The NEWCP will need to give due consideration to such a possibility. The phenomena whereby a countermeasure has unanticipated effects upon future ECM engagements will be referred to through the use of the term "latency".

A related issue that merits consideration is the possibility of interaction between different countermeasures. For instance, a chaff cloud, deployed in order to prosecute threat A may affect the behaviour of threat B which is being prosecuted by an on-board jammer. Clearly, threat B behaviours might be observed that can not be accounted for by the activities of the jammer. Effectiveness assessment in such a situation will have to account for such effects and this is clearly an issue that is only meaningful at a high level where a knowledge of the overall tactical situation can be brought to bear on the effectiveness assessment question.

Yet another high level issue associated with effectiveness assessment at a high level involves the possibility that a specific ECM tactic may achieve successful results in more than one way. For example, a chaff cloud initially sewn for the purposes of confusion may, as the result of changes in wind direction and speed, ultimately softkill the threat through the mechanism of a seduction effect. The NEWCP must have the flexibility to deal with such possibilities.

Because of the high degree of context dependency associated with the elaboration of effectiveness assessment functionality, it has been decided that high level effectiveness assessment will be addressed in a context-dependant manner. Accordingly, the material in chapters 4 and 5 will

describe effectiveness assessment in a variety of contexts. A fundamental issue that arises in this regard is the set of terms in which this context will be specified. The problem domain has a number of free variables that can each assume a large number of values; the most important variables being the threat parameters and the parameters that characterize the ECM reaction chosen.

The following section provides visibility into another high level issue that affects the elaboration of effectiveness assessment functionality. More specifically, this section addresses the relationship of the effectiveness assessment function to the other main function of the NEWCP: EW Deployment and Control.

2.4 Interaction Between Effectiveness Assessment Function and EW Deployment and Control Function

Another aspect of the context dependency associated with effectiveness assessment involves the existence of a higher level context within which the EW deployment and control function and the EW effectiveness assessment function interact. We have already seen that lower level effectiveness assessment activities, such as measuring seeker jogs and trajectory deviations, are not sufficient to render a judgement concerning engagement outcome: higher order knowledge is required. Even if account is taken of high level tactical parameters in the execution of effectiveness activity, the picture is not yet complete.

The scope of the context in which effectiveness assessment is performed includes elements other than higher level tactical information that is specifically relevant to the determination of engagement outcome. A complete treatment requires that proper account be taken of the relationship of the effectiveness assessment function to the EW deployment and control function. It can be readily seen that the EW deployment and control function confers very specific requirements upon the EW effectiveness assessment function.

The reason for this is that these two primary NEWCP functions exist and interact with each other in a higher level context. The issues which serve to define this higher level context consist primarily of the threat scenario and the fundamental tactical purposes for the deployment of EW. This higher level context imposes speed and sensor performance requirements upon the EW effectiveness assessment function. The underlying reasons for this relate ultimately to the tactical purpose for deploying EW and the constraints imposed by the threat scenario. The mechanism by which this higher level context confers performance requirements upon the EW effectiveness assessment function is perhaps best illustrated by the following representative example.

Consider a single threat (aircraft launched missile) attacking a single ship. A high level strategy for engaging this threat has been generated by the Command and Control System (CCS). Assume that this strategy can be summarized as follows:

- Engage the threat with EW;

- If ineffective, use hardkill weapons (e.g. SAM, CIWS)

The CCS will designate the target to the NEWCP who will be responsible for generating a strategy to defeat this threat. Let us assume that the NEWCP generates the following strategy for defeating the threat:

- Deploy chaff decoys with the goal of causing the targeting radar to acquire a chaff decoy, assess effectiveness;
- If ineffective, deploy a seduction countermeasure (e.g. RGPO + seduction chaff), assess effectiveness;
- Inform CCS of overall EW engagement result (failure / success)

The overall strategy selected by the CCS and the threat engagement timeline will clearly have an influence on the execution of effectiveness assessments. In this example, the CCS can wait only so long before exercising its option to use hardkill (this time constraint will likely be passed to the NEWCP as part of the target designation). Accordingly, the NEWCP is effectively constrained to execute its EW strategy within a fixed time interval.

It can be seen that the magnitude of this time interval will be directly influenced by threat parameters; for example, fast threats detected at close range will provide much less time for the NEWCP to react than slow threats detected at long range. Part of the execution of the NEWCP's EW strategy is the assessment of effectiveness; hence threat scenario parameters will influence the time available for performing this activity.

In addition, the specific details of the EW deployment strategy will confer performance requirements upon effectiveness assessment. In this example, the NEWCP has implemented a layered defence approach - from the fixed time available, the NEWCP must budget time to assess the effectiveness of each of the components of its overall strategy. Had a different strategy been selected, possibly with different component EW deployments and / or a different number of such deployments, the amount of time available for effectiveness assessment for each component would be different.

It may be worth underscoring that the threat scenario and the EW deployment strategy will not only determine the magnitude of the time interval available for effectiveness assessment, it will also determine the temporal position of this interval in the overall engagement timeline.

For example, suppose that the NEWCP is told by the CCS that it must execute its strategy between $t=0$ and $t=70$ seconds. This time interval will likely have been determined by the threat's engagement timeline; at $t=70$, the decision to use hardkill can be postponed no longer. Further let us assume that it takes 30 seconds for the first component of the EW strategy to affect the threat, while it takes 20 seconds for the second component to affect the threat. At $t=30$,

effectiveness assessment will be initiated for the first EW deployment. In this simplified example, a total budget of 20 seconds is available for EW effectiveness assessment ($70 - (30 + 20)$). If the time available is split evenly, effectiveness assessment for the first EW reaction will take place in the interval [30 s - 40 s] while effectiveness assessment for the second deployment, if this deployment is needed, will take place in the [60 s - 70 s].

The purpose for presenting this example is simply to demonstrate that the threat scenario and the EW strategy selected will impose constraints on EW effectiveness assessment. Clearly, these factors impose time constraints upon the execution of effectiveness assessment. By extension it can be readily seen that sensor performance requirements are also affected by the threat scenario and the EW deployment strategy.

In the example timeline provided above it was indicated that effectiveness assessment for the first EW deployment will take place in the interval [30 s - 40 s]. During this time interval, let us assume that the threat's range decreases from 40 to 30 km. In order to properly support effectiveness assessment, in this example, sensors must be capable of measuring relevant threat parameters at these ranges.

The numbers of different permutations and combinations of threat scenarios and EW deployment strategies are virtually infinite. Accordingly, it is not possible to quantify, in any simple kind of way, the performance constraints conferred upon effectiveness assessment by these factors.

In conclusion, the coupling between the Effectiveness Assessment and EW Deployment and Control functions of the NEWCP should be accounted for in future work involving the development of both Effectiveness Assessment and EW Deployment and Control algorithms. One particular implication of this coupling relates to the fact that sensor performance requirements are to some degree determined by the algorithms and constraints that govern the deployment and control of EW assets.

The following section provides insight into the manner in which high level effectiveness assessment functionality will be addressed within the body of this report. In particular, an introduction will be provided to the material provided in chapters 4 and 5.

2.5 Method for the Specification of High Level Effectiveness Assessment Functionality

As indicated above, high level effectiveness assessment is an activity that cannot be addressed without specific reference to a context within which the activity is performed. A determination of the terms by which this context will be elaborated is required.

Another requirement that must be addressed involves a specification of the roles of the various CPF sensors in supporting kill assessment. In particular, the capabilities of the sensors to support kill assessment must be addressed within the framework defined by the context specification as discussed in the preceding paragraph.

After some preliminary analysis, it was decided that the specific ECM tactical objective is the variable which essentially establishes the principal features of the context. Accordingly, a set of representative ECM tactical objectives has been established as follows:

- Deny the targeting platform the information that it needs to perform its targeting function;
- Cause the targeting platform to acquire decoy targets;
- Deny the threat (i.e. the missile) the information that it needs in order to detect and lock-on to the threat;
- Cause the threat to acquire decoy targets;
- For threats that have locked onto the ship, introduce tracking errors into the threat's tracking system in order to ensure that the threat misses its target ship;
- For threats that have locked onto the ship, introduce breaklocks and present the threat with a variety of alternate targets for subsequent acquisition;
- For threats that have locked onto the ship, seduce the threat tracking gate onto a specific decoy.

For a more detailed explanation of each of these tactical purposes, please refer to sections 4 and 5 of this report.

For each of the tactical objectives listed above, a set of representative techniques has been identified. For example, the use of RGPO and chaff is a technique which can support the tactical objective of seducing the threat seeker away from the ship. Figure 2-1 provides a structural framework within which both the tactical objectives and the specific ECM techniques are represented. The various tactical objectives are represented in this diagram under the heading "Desired ECM Result". The diagram links the various tactical objectives to radar types and their associated modes of operation. Finally, the diagram provides a linkage between specific ECM techniques and lower level techniques for effectiveness assessment.

A two stream approach to the elaboration of high level effectiveness assessment has been selected. The first stream, represented by the material provided in chapters 4 and 5 of this report, addresses primarily the roles of CPF sensors in supporting effectiveness assessment. The level of presentation is that of the tactical objective. For each tactical objective, the set of low level effectiveness assessment techniques required to support a higher level assessment is identified. For each such low level technique, the capabilities of CPF sensors to support effectiveness assessment is addressed.

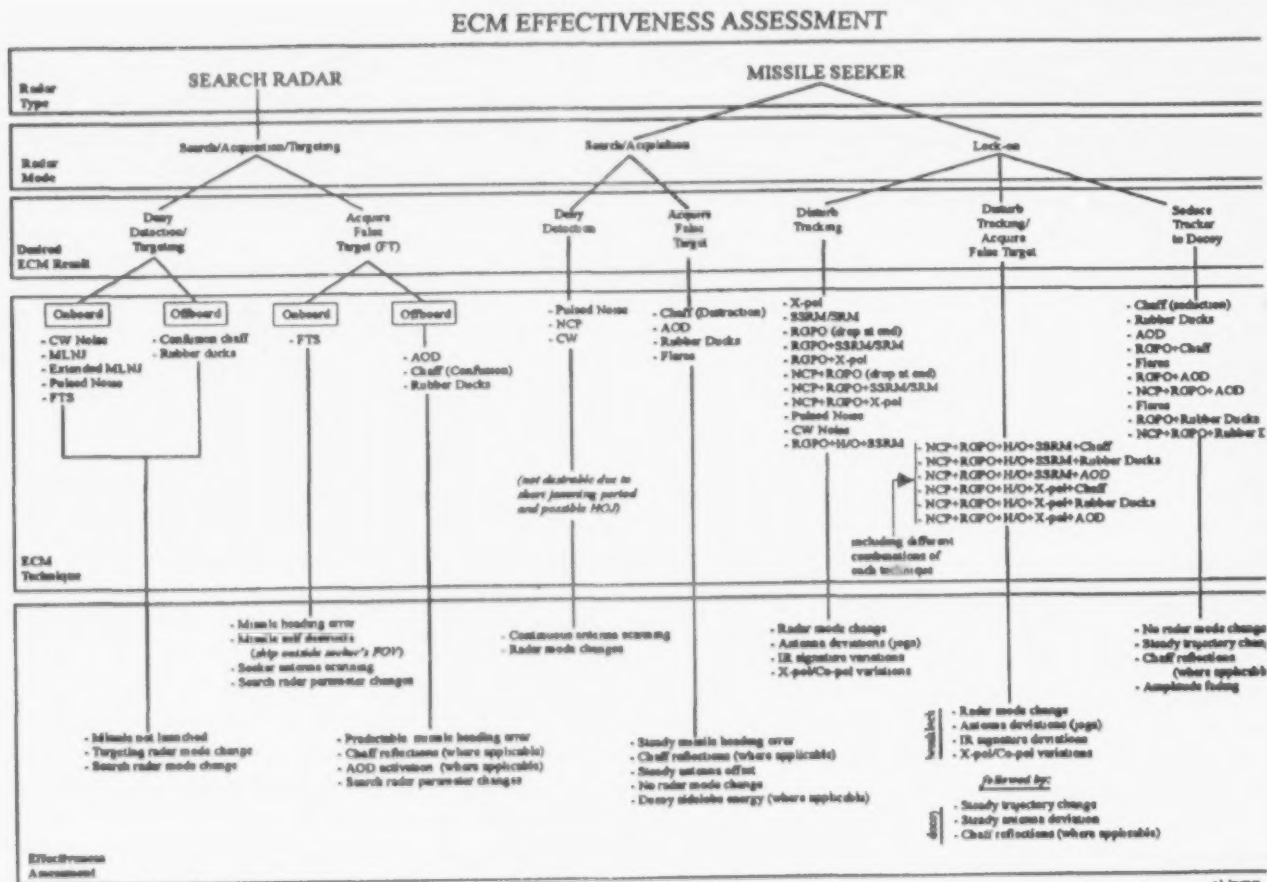


Figure 2-1 ECM effectiveness assessment techniques matrix

It may be important at this point to alleviate possible confusion between the material in chapter 3 and that to be provided in chapters 4 and 5. Although the material in the latter two chapters involves an indication of how CPF sensors contribute to low level effectiveness assessment techniques, the presentation is made within a specific tactical context. By comparison, the material provided in chapter 3 is generally presented in a manner that is independent of tactical context.

2.6 Representative Examples

The remainder of the material in this chapter will consist of two illustrative examples of some of the ECM effectiveness assessment issues enumerated above.

Consider first the deployment of confusion chaff. The purpose here is to cause the threat (which is in search mode at the beginning of the deployment) to detect, acquire, and lock-on to the chaff. As a result of so doing, the threat will change direction and head for the chaff cloud. Consider how chaff reflection measurements could be used in order to determine whether this sequence of events has indeed taken place.

The conclusion that environmental RF signals are consistent with a chaff softkill of the target can be viewed in terms of the combined effect of evidence. The following are pieces of evidence that would tend to support a determination of effective softkill;

- RF signals above background are observed;
- These signals are coming from the general direction of the chaff cloud;
- The appearance of these signals is roughly correlated in time with the deployment of chaff;
- The spectral characteristics of the RF signals are **roughly** consistent with those that might be associated with a threat seeker (e.g. generally in I band, etc.)
- etc.

Consider, by contrast, the deployment of seduction chaff. The purpose here is to introduce chaff into the seeker gate of a threat that is already in lock-on against the ship. The desired outcome is that the chaff cloud separates from the ship and "takes the seeker gate with it."

As before, the conclusion that environmental RF signals are consistent with a chaff softkill of the target can be viewed in terms of the combined effect of evidence. The following are pieces of evidence that would tend to support a determination of effective softkill;

- RF signals above background are observed;

- These signals are coming from the general direction of the chaff cloud;
- The appearance of these signals is roughly correlated in time with the deployment of chaff;
- The spectral characteristics of the RF signals are consistent with those associated with the threat that had been in track mode against the ship.
- etc.

It is seen that there is a difference in the way chaff reflection information is used to support a determination of softkill, depending upon whether a tactic of seduction is used as compared to a tactic of confusion. The particular difference in this example relates to what we know about the threat's spectral characteristics - in one case we can use detailed specific information while in the other case we must limit ourselves to generic values.

This example illuminates the fact that the various effectiveness assessment techniques cannot be viewed in isolation from the context in which they are used. It also illustrates that while the notion of a two level hierarchy of effectiveness assessment is very useful, there can be some "tangling" of these levels. In this case, the low level effectiveness assessment operation of comparing spectral characteristics to expected values has some context dependency.

Consider a second example again involving the deployment of confusion chaff. The observation of chaff reflections might be taken as a sign that a threat has been successfully decoyed by the chaff. However, it is also possible that a second threat, possibly with active radar spectral characteristics similar to the first, has turned on its radar and is illuminating the chaff cloud. In this case, the first threat may still be locked onto the ship. Failure to account for higher level tactical knowledge, not directly relevant to the specific interaction between chaff and the first threat and that might indicate the presence of a second threat may lead to an erroneous EW effectiveness assessment.

2.7 Sensor Data Fusion

The optimal use of combat environment information provided by the ship's sensors is critical to performing ECM effectiveness assessment. In particular, a capability to rapidly and accurately characterize the behaviour of the threat is needed to support effectiveness assessment. This requirement gives rise to the need for an effective sensor data fusion capability.

Sensor data fusion supports effectiveness assessment through the timely provision of an accurate description of the tactical environment (the threat in particular). The fusion of sensor data improves the completeness of the data set used to perform effectiveness assessment. For example, a sensor data fusion capability allows for the fusion of range and bearing information from a 2-d radar with the bearing and elevation information from anIRST sensor in order to

arrive at a 3-d description of the target. Furthermore, sensor data fusion improves the timeliness of threat characterization by exploiting the capabilities of all ship-borne sensors rather than relying on a single sensor whose target characterization capabilities may be inferior to those of other ship-borne sensors or whose performance may be degraded by weather. Finally, sensor data fusion improves the accuracy with which the tactical environment is characterized by combining information provided by a variety of sensors, each with its proper accuracy characteristics.

All these capabilities are required in order to perform effectiveness assessment. This is particularly true in light of the fact that modern ASM threats place severe time constraints upon the execution of the effectiveness assessment function and that environmental and other factors invariably introduce uncertainty and ambiguity into any attempts to characterize the tactical environment.

2.8 Overview of Sensors

This section provides an overview of the various sensors currently aboard the CPF and those envisaged for possible fitment during the ship's mid-life upgrade. A more detailed description of these sensors can be found in the NEWCP "Equipment Study" interim report, June 1993, submitted to DREO. Figure 2-2 provides a matrix of each sensor and their potential relevance towards supporting the various ECM effectiveness assessment techniques described in section 3 of this report. The 'P' signifies a primary role for the sensor, while 'S' indicates a secondary role.

The radars currently fitted on the CPF include the SPS-49 long range air surveillance radar, with its integrated IFF system, SG-150 HC Sea Giraffe medium range search radar, two separate tracking and illuminating radars (STIR) for tracking air and surface targets at short and medium range, the MK-340 navigation radar, and the automatic search/track radar associated with the Mk 15 close in weapon system (CIWS). The APAR multifunction radar (MFR) is currently being designed and built for fitment aboard the CPF. A future radar which could be implemented includes the low probability of intercept (LPI) radar.

Other sensors aboard the CPF are the CANEWS ESM system, as well as the ESM subsystem of RAMSES, and the subsurface acoustic detectors, including the hull mounted sonar (HMS) system, the sonobuoy processing system (SPS), and the Canadian towed array sonar system (CANTASS).

Future sensors that could be fitted include a high accuracy direction finding (HADF) system, in conjunction with an upgraded CANEWS ESM system, and an infrared search and track (IRST) system.

Equipment	Initial Detection				Logs			Radar mode change	Trajectory Deviations			Chaff Cloud Reflection	Missile Kill Assessment	Comments P = Primary role S = Secondary role
	Missile	Ship	aircraft	sub	amp	radar reflections	X-pol/co-pol		position	doppler	Apparent missile length Δ			
SFS-49	P	S	P						P ¹					1. Crude measurements
Sea Gnat	S ¹	S							S ¹					1 High direct 2 Crude measurements
STIR	P	S	P			P			P	P			P	
CIWS		S												
ESM	P ¹	P ¹	P ¹		P		P ¹	P		S		P	S	1 For active seekers only 2 If radar/ECM are transmitting 3. With dual polarised antenna
Sonar		P		P									S	
IFF		S	S											
MK-340		S ¹												1 Support TSA at short range
HADF														
IRST	S ¹								P ¹			P ¹		1. For active seekers only 2. For chaff discrimination
MFR	P	P	P			P			P				P	1. < 20 km
LPI	P	P	P			P			P					
Helicopter (visual)	S	P	P	S					S					

Figure 2-2. Summary of sensors supporting ECM effectiveness assessment

3.0 Low Level Effectiveness Assessment

3.1 Radar Mode Changes

This section describes the different operating modes of targeting radars and missile seekers and the mode changes they can experience when exposed to electronic countermeasures. A mode change is typically characterized by a variation in certain parameters of the radar such as frequency, PRI, pulse width, antenna scanning profile (scan limits/rate), transmitter state (on/off), etc. In principle, the NEWCP should be able to correlate the measured parameter changes with a specific mode of the radar to determine the effectiveness of ECM.

3.1.1 Targeting radars

The launch platform may use its own radar or a third party system to obtain a fix on its intended target (own ship) for missile designation. In both cases, the targeting radar is controlled by an operator, who views a planned display (PPI scope) to obtain range and angle information on the target. The antenna of the targeting radar is usually a scanning type, so that the operator has a full view of the tactical environment at all times. Some radars are track while scan (TWS) systems, in which the antenna continually scans or rotates in one direction while target track is silently established and maintained by the operator (a Kalman filter or similar processor may be utilized to achieve automatic tracking). In this case, the NEWCP has no direct way of knowing when own ship has been detected, or if a decoy has been effective in fooling the operator. Some radar antennas scan bidirectionally over a specified sector, as defined by the operator. The operator may choose narrow angle limits if he/she has high confidence in the tactical picture, or broad limits if there are too many targets from which to choose a valid one or if jamming exist. The NEWCP may derive from changes in scanning behaviour that the operator is possibly being affected by jamming or is unsure of the location of own ship.

Under prevalent noise jamming conditions, the enemy operator may resort to altering radar parameters to minimize or remove the effects of ECM, such as shifting frequency away from the operating bandwidth of the noise jammer. In this case, the NEWCP, with its ESM system, should detect the parameter change, providing a strong clue that noise jamming is having an adverse affect.

For certain third party radars, such as the HORMONE radar associated with the Bear-D helicopter, its transmit parameters change when targeting information is being sent to the launch platform. In this case, NEWCP can deduce from the specific change in measured parameters that a missile attack is imminent, signifying ECM was likely unsuccessful.

3.1.2 Missile Seeker

The principal modes of a seeker are: off, search, acquisition, home-on-jam (HOJ), track (lock-on), and reacquisition. Refer to figure 3-1 for a state transition diagram of the various modes of the seeker. The following diagram, figure 3-2 depicts the parameters that can be measured by own ship's sensors to support effectiveness assessment of each radar mode change.

Search Mode

The seeker enters into search mode immediately upon activation, which usually occurs when the missile reaches the target's estimated radar horizon, i.e. 25 - 40 km. The seeker searches for its target by sweeping its antenna in azimuth between pre-defined limits and in range. The limits are set by the launch platform which determines the uncertainty in target position relative to the missile's heading at seeker activation. Typical initial angular limits are ± 5 deg. During this mode, the missile flies in auto-pilot, based on a pre-programmed trajectory.

If no target is detected, then the seeker may broaden its sweep limits up to the antenna's maximum field of view (FOV), usually on the order of ± 15 deg. The NEWCP would detect the broader angular sweeps by noting, through ESM measurements, that the seeker signal fades, due to scanning, are occurring over a longer period of time than before. This would provide a clue that the current ECM technique may be effective in preventing the missile from establishing a fix on own ship. If a target is still not detected after a certain period of time, then the missile may fly into the water or self-destruct. Again, NEWCP, with the appropriate sensors, would be able to discern that the missile was likely defeated as a result of ECM.

Besides the initial entry from seeker activation, search mode can also be entered from the following modes: HOJ, track (for search while track radars), acquisition, or reacquisition.

If a potential target is detected, then the missile enters into acquisition mode to determine if the target is valid.

Acquisition

The acquisition mode is primarily entered from the search mode, where the seeker has made target contact and now attempts to determine the validity of the target return signals. The seeker antenna remains fixed on the target for a certain period of time while onboard logic determines if the echo returns are consistent with the desired target ship, or if ECM is present. For seekers with multiple range gates, several potential targets within the mainbeam may be interrogated to determine which one is valid or has the highest priority.

The missile is still flown under auto-pilot during this phase of the seeker. The acquisition mode occurs very quickly, on the order of 1-2 seconds, depending on the density of the tactical environment. If a valid target is not detected, then the seeker returns to search mode, using

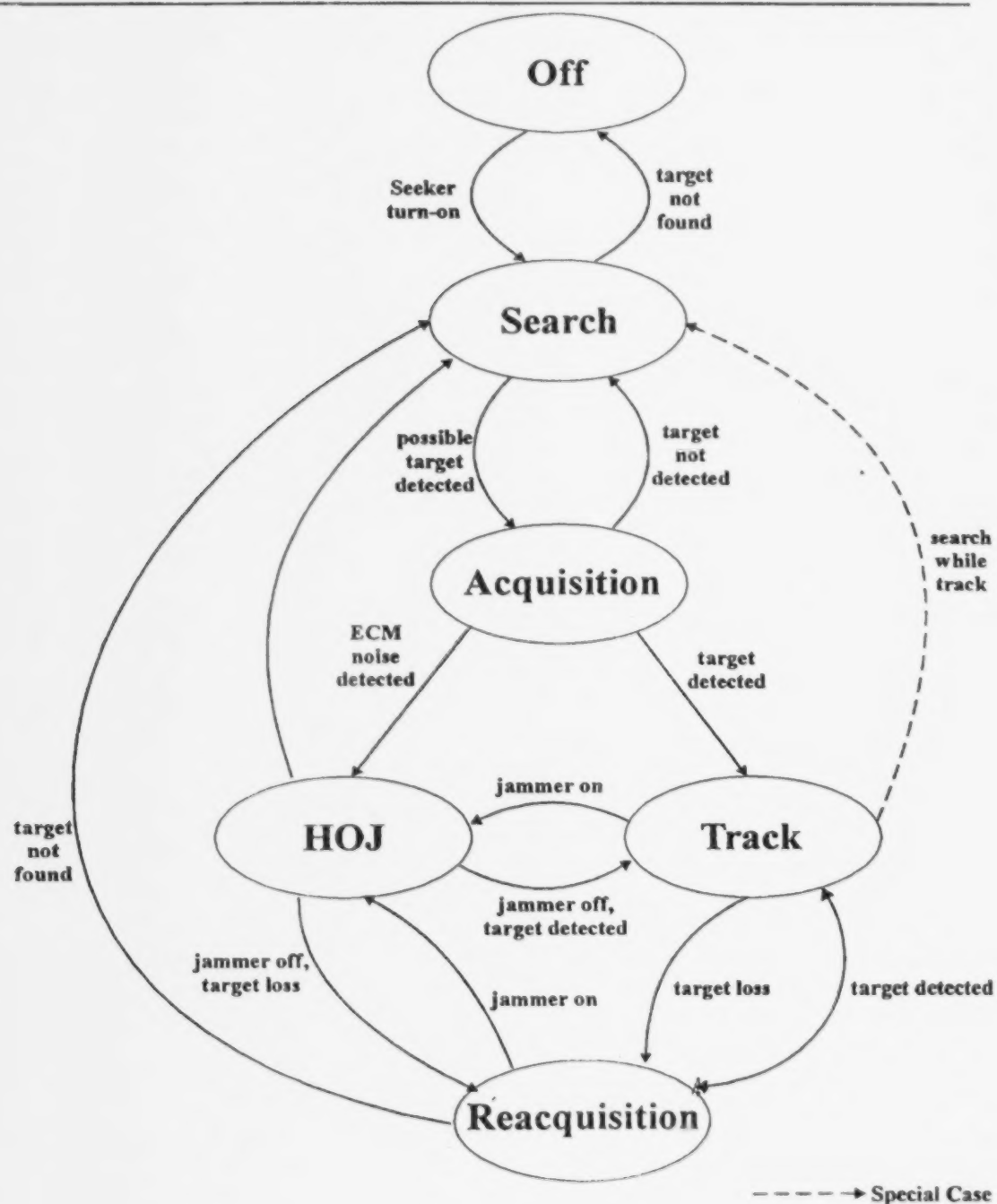


Figure 3-1 State transition diagram for seeker modes

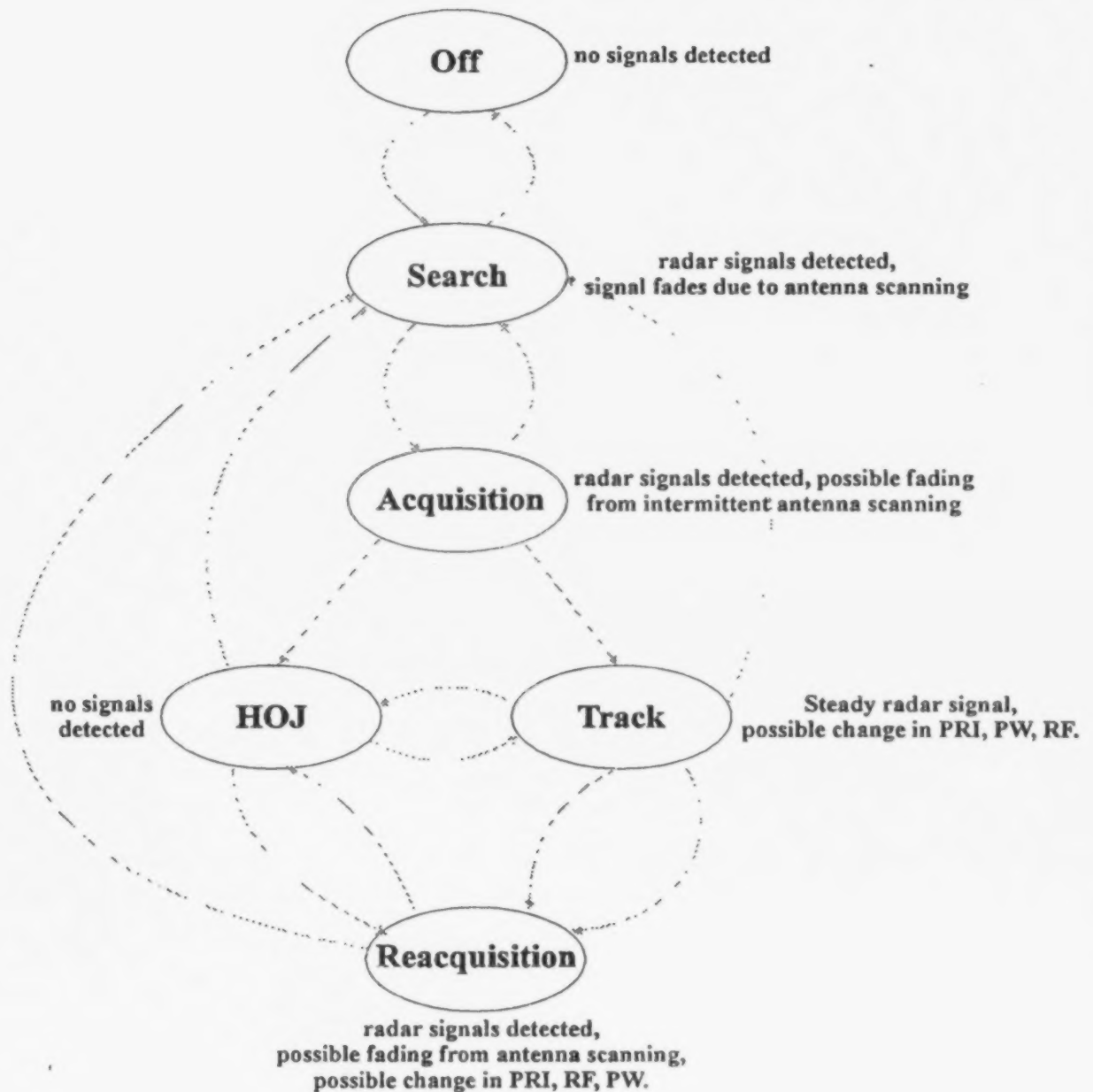


Figure 3-2 Measured parameters for different radar modes

narrow limits as discussed above. In this case, the NEWCP should detect the sudden scanning, signifying that ECM was possibly successful. If the target (own ship) is detected, then the seeker will leave acquisition mode and enter into track mode. On the other hand, if noise jamming is present, the missile will enter into home-on-jam mode.

Track

Once the target has been acquired, the seeker enters into track mode, where it pursues the target in range and angle, providing guidance data to the missile. In some cases, the missile may continue to fly a pre-programmed height profile until the last few moments of impact, to better evade ship's defence and penetrate the ship at its most vulnerable point, as pre-defined by the launch platform. Since the seeker is in track mode, its antenna no longer scans, therefore, the ESM system should not measure any signal fades indicative of antenna scanning. Multipath fading may cause some ambiguity in measurement, therefore, NEWCP will have to ensure the fades are consistent with environmental anomalies rather than antenna scanning. In addition to the non-scanning of the seeker antenna during track mode, the seeker may also vary some of its parameters, and introduce frequency agility and/or PRF jitter/stagger to minimize vulnerabilities to ECM, among other things.

The seeker may exit track mode and enter into HOJ mode if noise jamming is present. The seeker senses noise by measuring the return signal in special guard gates displaced in range from the primary range gate. For noise cover pulses, the seeker may maintain an estimate of the targets range, so that when the jammer turns off, the primary gate will be on top of the ship for immediate lock-on. For CW noise, the seeker can only track in angle, using special circuits, and must reacquire the ship once the noise signal disappears.

The seeker may leave track mode and enter into reacquisition mode if the target being tracked in the primary range gate is suddenly lost. This condition may occur as a result of range gate pull off (RGPO), where the range gate is seduced away from own ship and dropped off.

For search-while-track (SWT) systems, where multiple range gates are employed, the seeker may also exit track mode momentarily to perform a search for other possible targets in the vicinity. In this case, periodic signal fades, resulting from antenna scanning, may be detected at own ship to provide a clue that the seeker is in SWT mode.

Reacquisition

The seeker enters reacquisition mode from track mode, when the target signal disappears, or HOJ mode, when the noise jammer is turned off. A search in range is usually performed about the last known position of the tracked target. In some cases, a fine angular search may also be performed for targets that may have deviated in bearing prior to the break-lock.

The seeker will enter into track mode or HOJ mode, if either the target or noise signal is re-

detected, or into search mode if no signals are detected.

Home-on-Jam

The seeker operates in home-on-jam mode when a noise signal is detected, and may be entered from either acquisition, track, or reacquisition mode. During HOJ, the missile achieves guidance by passively tracking the noise signal. A seeker which stops transmitting immediately after noise jamming may provide a clue to the NEWCP that the seeker has entered into HOJ mode. This is tactically desirable providing the noise signal is originating from a decoy, otherwise, the seeker may still impact the ship if it is pursuing the noise emanating from the onboard jammer. A common tactic is to intermittently turn on/off the jammer so that the missile's overall tracking performance is degraded.

The seeker may exit HOJ mode when the noise is turned off or disappears (e.g. due to multipath), and enter into one of the following modes: i) track mode if the pulsed noise disappears and the primary range gate falls on the target, ii) reacquisition mode if the noise signal disappears and no target is detected, or iii) search mode if the noise signal disappears, no target is detected, and the tactical picture is uncertain.

3.2 Missile Trajectory Changes

3.2.1 Direct Measurement of Threat Trajectory Changes

3.2.1.1 Introduction

The purpose of this section of the report is to provide visibility into the use of threat trajectory measurements in order to support EW effectiveness assessment. In this section, consideration is given to the direct measurement of trajectory changes by using the positional target characterizations as provided by the sensors. Other, more indirect methods, for inferring target trajectory changes are addressed in Sections 3.2.2, 3.2.3, and 3.2.4.

The primary function of many EW systems is that of decoying the threat away from ownship and towards a decoy (e.g. chaff, active off-board decoy). Ship sensors can be used to measure threat position over time and hence support a determination of whether threat trajectory is consistent with successful decoy action. Later in this section, the framework will be provided for a method that uses trajectory measurements to assign a probability value to each of a set of mutually exclusive hypotheses about the outcome of the engagement.

Sensor accuracy is a fundamental limiting factor associated with the use of trajectory deviation measurements in support of effectiveness assessment. The ability of a sensor to detect a change in target heading is directly related to its ability to accurately characterize target angular position as measured from the ship. If a sensor has poor angular accuracy, it may not be possible to determine whether changes to measured target azimuth / elevation should be attributed to the

sensor inaccuracy or changes to target motion. To a first approximation, it can be stated that if apparent changes to target angular position exceed the sensor's angular accuracy, then it can be concluded that the target has indeed changed its trajectory.

There is a temporal dimension to the measurement of target angular position that will be clarified by example. Consider a closing target whose angular position in azimuth has been measured as $= 90^\circ$ over some reasonable period of time (e.g. 10 seconds). It can be concluded that this target is radial in-bound. If a decoy is deployed successfully, the threat will alter its heading and navigate towards the decoy. As it does this, measured target azimuth should begin to change. As time proceeds, the difference between measured target azimuth and the target azimuth that would indicate a radial in-bound trajectory will increase. This difference angle will increase with time and once it exceeds the azimuth measurement accuracy of the sensor in question, it can reasonably be assumed that the threat has indeed changed its trajectory.

The main body of the material in this section provides an overview of a method for using target trajectory measurements to assign a probability value to each of a set of mutually exclusive hypotheses about engagement outcome. This method is based upon the use of sensor measurements to predict the Closest Point of Approach (CPA) of the target to the ship and the decoy(s). It should be underscored that the CPA represents a prediction about the future: target measurements are extrapolated using an assumed model for target behaviour. A commonly used model is that of straight line motion: it is assumed that the target will continue on its current heading. Using current target measurements (including heading) as well as a model for future target motion, CPA with respect to both decoy and ship can be calculated using straightforward geometrical reasoning.

3.2.1.2 Representative Threat Trajectories

Before presentation of this method, however, visibility will be provided into typical trajectory profiles associated with representative threats and representative EW deployments. These will provide an indication of the trajectory changes that the NEWCP will need to characterize. Trajectory deviations will be presented in terms of how an angle β varies with time within the context of a particular threat scenario and EW deployment. The angle β is alluded to above and is defined as angle between the following two lines:

- (1) The line that defines a radial in-bound trajectory that the threat would follow were the EW deployment unsuccessful; and,
- (2) The line that defines the measured line-of-sight to the target.

Figures 3-3, 3-4, and 3-5 provide representative trajectories for two of the threats defined at in the Threat Study. In particular, the threats represented include the SS-N-22 type threat (surface-launched supersonic medium range sea skimming missile) and the SS-N-19 type missile (surface-launched supersonic long range missile). Trajectories are computed within the context of three

different EW tactical objectives: confusion, distraction/dilution, and seduction. The graphs provide a representation of the angle β (described above) as a function of the independent variable time.

A simulation model, incorporating a proportional navigation model for threat flight, has been used and it has been assumed that the threat is successfully decoyed at $t = 0$ in each case. Tables 3-1, 3-2, and 3-3 provide further specification of the test conditions for the distraction, confusion, and seduction cases respectively. In each case, chaff has been used to achieve the tactical objective and the chaff is assumed to move with the wind. The simulation model, while relatively simple, provides a quantification of representative threat trajectory deviations.

The reader may notice that for the seduction case, the magnitude of β initially decreases with time. This is due to the fact that the chaff cloud is initially deployed about 100 m from ownship at $t=0$ and then passes over ownship before ultimately moving away from ownship as desired.

TABLE 3-1: Distraction Test Conditions

	SS-N-22	SS-N-19
Decoy Initial x-coordinate	Classified	Classified
Decoy Initial y-coordinate	Classified	Classified
Decoy Vx	Classified	Classified
Decoy Vy	Classified	Classified
Threat Initial x-coordinate	Classified	Classified
Threat Initial y-coordinate	Classified	Classified
Threat Velocity	Classified	Classified
Threat Vx	Classified	Classified
Threat Vy	Classified	Classified
Ship Initial x-coordinate	Classified	Classified
Ship Initial y-coordinate	Classified	Classified
Ship Vx	Classified	Classified
Ship Vy	Classified	Classified
ProNav Constant	Classified	Classified

TACTICAL OBJECTIVE: XXXXXX

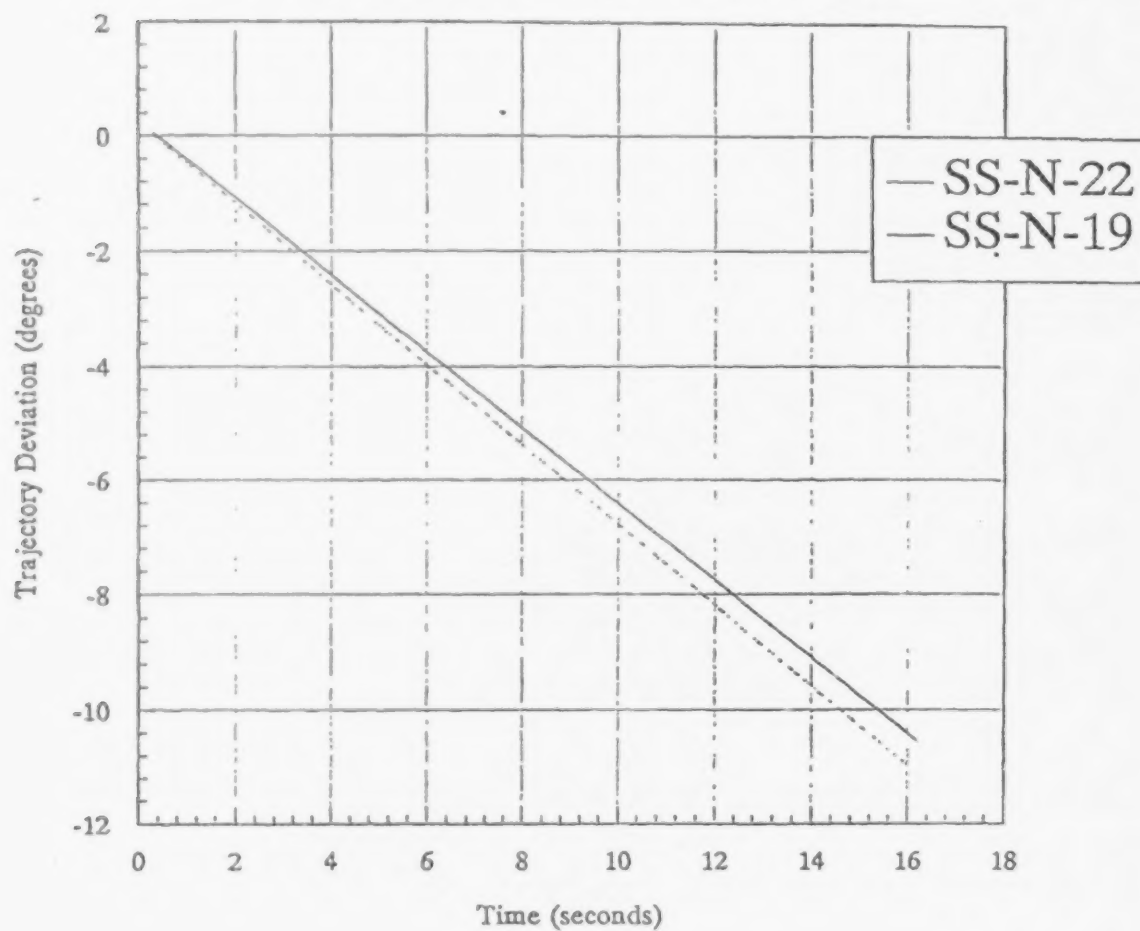


Figure 3-3 Representative Trajectory: Tactic = Classified

TACTICAL OBJECTIVE: XXXXXX

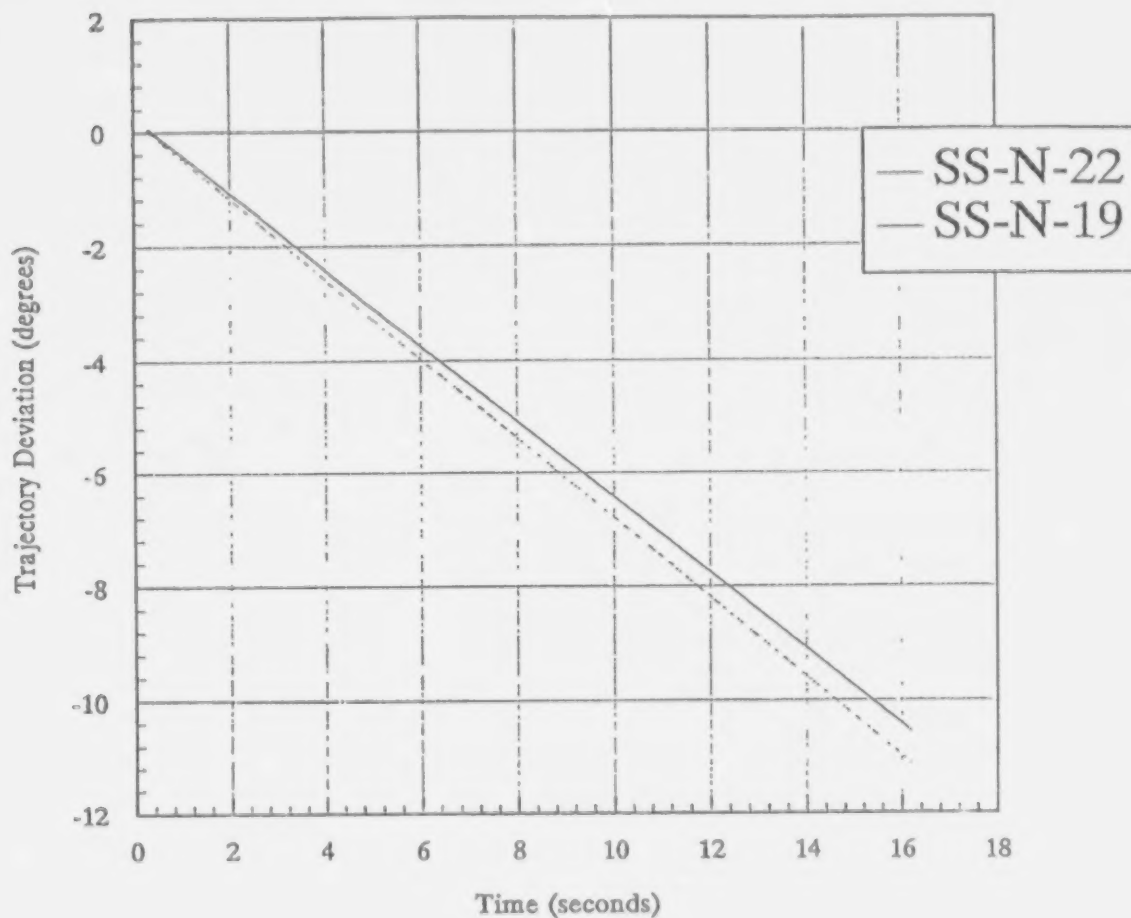


Figure 3-4 Representative Trajectory: Tactic = Classified

TACTICAL OBJECTIVE: XXXXXX

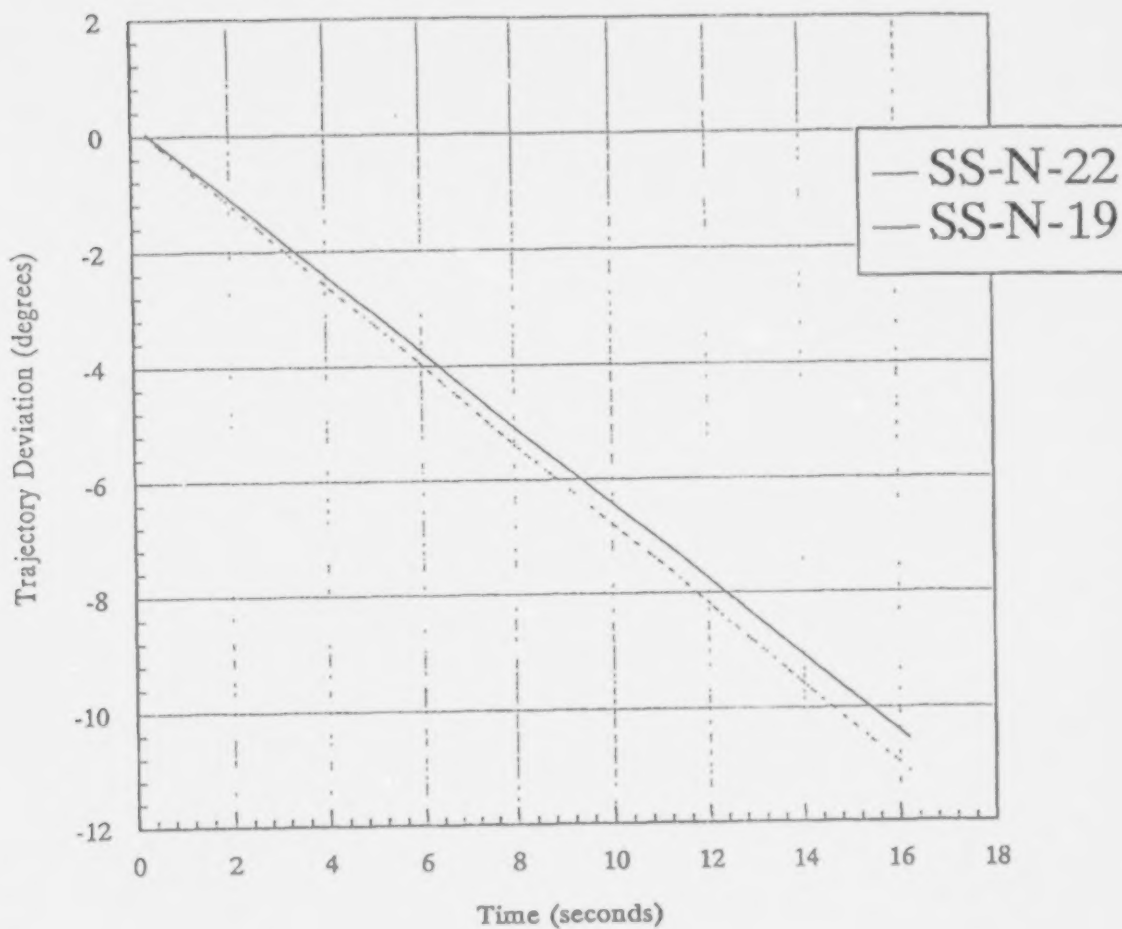


Figure 3-5 Representative Trajectory: Tactic = Classified

TABLE 3-2: Confusion Test Conditions

	SS-N-22	SS-N-19
Decoy Initial x-coordinate	Classified	Classified
Decoy Initial y-coordinate	Classified	Classified
Decoy Vx	Classified	Classified
Decoy Vy	Classified	Classified
Threat Initial x-coordinate	Classified	Classified
Threat Initial y-coordinate	Classified	Classified
Threat Velocity	Classified	Classified
Threat Vx	Classified	Classified
Threat Vy	Classified	Classified
Ship Initial x-coordinate	Classified	Classified
Ship Initial y-coordinate	Classified	Classified
Ship Vx	Classified	Classified
Ship Vy	Classified	Classified
ProNav Constant	Classified	Classified

TABLE 3-3: Seduction Test Conditions

	SS-N-22	SS-N-19
Decoy Initial x-coordinate	Classified	Classified
Decoy Initial y-coordinate	Classified	Classified
Decoy Vx	Classified	Classified
Decoy Vy	Classified	Classified
Threat Initial x-coordinate	Classified	Classified
Threat Initial y-coordinate	Classified	Classified
Threat Velocity	Classified	Classified
Threat Vx	Classified	Classified
Threat Vy	Classified	Classified
Ship Initial x-coordinate	Classified	Classified
Ship Initial y-coordinate	Classified	Classified
Ship Vx	Classified	Classified
Ship Vy	Classified	Classified
ProNav Constant	Classified	Classified

3.2.1.3 Introduction to Multiple Hypothesis Method for CPA-based Effectiveness Assessment

One possible method for using trajectory measurements in support of softkill effectiveness assessment involves making predictions, based upon sensor measurements, about the closest point of approach (CPA) of the threat to various objects in the environment (e.g. ownship, decoys). The predicted CPA can then be used within the context of a *multiple hypothesis test* in order to decide whether the threat is heading towards ownship, a decoy, or neither. This sub-section of the report provides visibility into this method and addresses a possible enhancement that will improve performance. The methodology presented is based upon a paper produced by S.A. Cohen of the Applied Physics Laboratory (APL) associated with Johns Hopkins University. Simulation results presented are those performed at APL.

The methodology presented essentially deals with the issue of selecting a single hypothesis from amongst a set of hypotheses that collectively serve to characterize the possible outcomes of an EW engagement. Predicted CPA values, measured with respect to both ownship and a decoy, are used within this multiple hypothesis paradigm, to select what is considered to be the most likely hypothesis concerning engagement outcome. Clearly the performance of the methodology is of central interest: In this context, the performance of a method for softkill effectiveness assessment is defined in terms of the degree to which the predicted outcome of the engagement (i.e. the selected hypothesis) matches the actual outcome of the engagement. For the methodology being presented, the issue of performance will be addressed through the provision of the results of simulation tests.

As will be seen from the results of simulation studies, the accuracy of ownship sensors directly influences the performance of the proposed methodology. This is not surprising given that the degree to which the tactical picture constructed by ownship reflects reality is directly related to the accuracy with which sensors characterize objects in the combat environment.

3.2.1.4 Analysis - Multiple Hypothesis Method

As indicated above, the proposed softkill effectiveness assessment algorithm is based upon the notion of a multiple hypothesis test. The problem of interest concerns evaluating the effectiveness of a single decoy (e.g. chaff) in inducing trajectory changes in a missile threat to ensure that it will not hit ownship. In this context we consider three high level hypotheses concerning engagement outcome. The first hypothesis is that the missile is heading for ownship and hence will have a $CPA = 0$ (measured with respect to the ship). The second hypothesis is that the missile is heading straight for the decoy. If the distance from the ship to the decoy is designated as D , then the CPA (measured with respect to the ship) associated with the second hypothesis should also $= D$. Finally, the third hypothesis is that the threat is neither heading for the decoy nor the ship. Let us designate these hypotheses as H_0 , H_D , and H_1 , respectively. Symbolically we have:

$$\begin{aligned} H_0: & \text{CPA} = 0 \\ H_D: & \text{CPA} = D \\ H_1: & (\text{CPA} = 0) \text{ and } (\text{CPA} = D) \end{aligned}$$

The CPA is calculated by extrapolating target position over time (assuming that ownship sensors provide threat position information and that threat velocity is either measured directly or calculated). Because there will inevitably be target tracking noise, the conditional probability that an arbitrary CPA, d_c , will be associated with hypothesis H_0 will have the following distribution, assuming a zero mean gaussian probability density:

$$p(d_c | H_0) = \frac{1}{\sqrt{2\pi}\sigma_c} \exp[-d_c^2 / 2\sigma_c^2] \quad (1)$$

where the variance associated with d_c is given in reference A by:

$$\sigma_c^2 = \left[1 + \frac{\gamma R^2}{(v \Delta t)^2} \cos^2 \epsilon - \frac{2R\beta}{v \Delta t} \cos \epsilon \right] (\sigma_r^2 \sin^2 \epsilon + R^2 \sigma_\theta^2 \cos^2 \epsilon) \quad (2)$$

where

R = range from ownship to target position corresponding to d_c ,

v = target velocity,

ΔT = target position data update time difference,

σ_r = sensor range accuracy,

σ_θ = sensor bearing angle accuracy,

β, γ = error reduction parameters of the tracking filter, and

ϵ = inbound/outbound angle

$$\epsilon = \sin^{-1} \frac{d_c}{R}$$

Similarly, the conditional probability that an arbitrary CPA, d_c , will be associated with hypothesis H_D will have the following distribution:

$$p(d_c | H_D) = \frac{1}{\sqrt{2\pi}\sigma_c} \exp[-(d_c - D)^2 / 2\sigma_c^2] \quad (3)$$

It should be remembered that, by definition, threat CPAs are measured with respect to ownship. Accordingly, if $d_c = D$, the threat is heading directly for the decoy and the above expression for conditional probability is maximized.

Under hypothesis H_1 , it is assumed that the CPA will assume any value in the interval $[-R, +R]$ with equal probability (i.e. a uniform probability distribution), where R is the current distance from the threat to ownship. A CPA $> R$ is not possible since the threat is already at a distance of R from ownship. The relevant distribution function is as follows:

$$p(d_c | H_1) = \begin{cases} 1/(2R) & -R < d_c < R \\ 0 & |d_c| > R \end{cases} \quad (4)$$

The physical interpretations of these probability distribution functions may require further elaboration. The variable d_c represents an arbitrary CPA value and is based on the extrapolation of sensor measurements under some reasonable target motion model (e.g. the threat will continue in a straight line trajectory). As such d_c is essentially an *observation*. The probability distribution function $p(d_c | H_0)$ is a characterization of the likelihood that the observation d_c is consistent with the hypothesis H_0 . Likewise the distributions $p(d_c | H_D)$ and $p(d_c | H_1)$ characterize the likelihood that the observation d_c is consistent with hypotheses H_0 and H_1 , respectively.

In accordance with the principal of multiple hypothesis testing, it is not *necessary* that the hypotheses be mutually exclusive. It is conceivable that an observation d_c lends to some measure of support to each of the three hypotheses under consideration.

With reference to the above probability distributions, two *likelihood ratios* can be defined as follows:

$$\Lambda_0(d_c) = \frac{p(d_c | H_0)}{p(d_c | H_1)} \quad (5)$$

$$\Lambda_D(d_c) = \frac{p(d_c | H_D)}{p(d_c | H_1)}$$

Reference B shows that such ratios can be used as thresholds for arbitrating among hypotheses and that the threshold of a test based on such thresholds is a function of a priori probabilities and cost assignments for being correct or not with respect to each hypothesis. If all decision errors are assigned equal importance, then the following decision expressions are proposed:

H_0 or H_D

$$\Lambda_0(d_c) \begin{matrix} > \\ < \end{matrix} P_1/P_0$$

H_1 or H_D

H_D or H_0

$$\Lambda_D(d_c) \begin{matrix} > \\ < \end{matrix} P_1/P_D$$

H_1 or H_0

H_D or H_1

$$P_D \Lambda_D(d_c) \begin{matrix} > \\ < \end{matrix} P_0 \Lambda_0(d_c) \quad (6)$$

H_0 or H_1

The a priori probabilities mentioned above and represented in these equations by the terms P_0 , P_1 , and P_D , have the following meanings:

P_0 : a priori probability that the threat will head for ownship;

P_D : a priori probability that the threat will head for the decoy; and

P_1 : a priori probability that the threat will head for neither ownship nor decoy.

Further elaboration on the interpretations of these decision expressions is warranted. Consider the first pair of statements from the list of decision expressions provided above. A value for $\Lambda_0(d_c) > 1$ means that the support provided to hypothesis H_0 by the observation d_c is greater than the support provided to the hypothesis H_1 . Let us provisionally assume that $P_0 = P_1$. The $>$ condition is then satisfied and we have effectively discriminated between hypotheses H_0 and H_1 (i.e. in favour of H_0). However, the first inequality pair does not render any judgment concerning hypothesis H_D . Accordingly, the outcome of the first inequality pair in this example (the $>$ condition being satisfied) is (H_0 or H_D). To understand that the combined effect of these decision expressions yields sensible results, the reader may wish to construct a scenario by providing values for $\Lambda_0(d_c)$, $\Lambda_D(d_c)$, P_0 , P_D , and P_1 and then evaluating all decision expressions.

Returning to the decision expressions provided above and expressing them in the form of (natural) logarithms of likelihood ratios, we obtain:

H_0 or H_D

$$\ln \Lambda_0(d_c) \begin{matrix} > \\ < \end{matrix} \ln(P_1/P_0)$$

H_1 or H_D

H_D or H_0

$$\ln \Lambda_D(d_c) \begin{matrix} > \\ < \end{matrix} \ln(P_1/P_D)$$

H_1 or H_0

$$\begin{array}{c}
 H_D \text{ or } H_1 \\
 \ln \Lambda_D(d_c) \quad \begin{array}{c} > \\ < \end{array} \quad \ln \Lambda_0(d_c) + \ln(P_0/P_D) \\
 H_0 \text{ or } H_1
 \end{array} \quad (7)$$

Now the ratios of a priori probabilities (e.g. P_1/P_0 , P_1/P_D) are effectively "thresholds" in the sense that they determine which of the decision expressions are satisfied. Let the thresholds associated with these likelihood ratio tests be denoted by η_0 and η_D as follows:

$$\eta_0 = P_1/P_0 \quad , \quad \eta_D = P_1/P_D \quad (8)$$

when the log-likelihood ratio (LLR) expressions become

$$\begin{array}{c}
 H_0 \text{ or } H_D \\
 \ln \Lambda_0(d_c) \quad \begin{array}{c} > \\ < \end{array} \quad \ln \eta_0 \\
 H_1 \text{ or } H_D
 \end{array}$$

$$\begin{array}{c}
 H_D \text{ or } H_0 \\
 \ln \Lambda_D(d_c) \quad \begin{array}{c} > \\ < \end{array} \quad \ln \eta_D \\
 H_1 \text{ or } H_0
 \end{array}$$

$$\begin{array}{c} H_D \text{ or } H_1 \\ \ln \Lambda_D(d_c) > \ln \Lambda_0(d_c) \\ H_0 \text{ or } H_1 \end{array} \quad (9)$$

with the assumption that $P_0 = P_D$ (a reasonable assumption for the problem at hand).

We now substitute the probability densities provided above into the log-likelihood ratio expressions:

$$\ln \Lambda_0(d_c) = \ln \left[\sqrt{\frac{2}{\pi}} \frac{R}{\sigma_c} \right] - \frac{d_c^2}{2\sigma_c^2} \quad \begin{array}{c} H_0 \text{ or } H_D \\ > \\ < \\ H_1 \text{ or } H_D \end{array} \ln \eta_0$$

$$\ln \Lambda_D(d_c) = \ln \left[\sqrt{\frac{2}{\pi}} \frac{R}{\sigma_c} \right] - \frac{(d_c - D)^2}{2\sigma_c^2} \quad \begin{array}{c} H_D \text{ or } H_0 \\ > \\ < \\ H_1 \text{ or } H_0 \end{array} \ln \eta_D$$

$$\begin{array}{c} H_D \text{ or } H_1 \\ d_c^2 > (d_c - D)^2 \\ H_0 \text{ or } H_1 \end{array} \quad (10)$$

The above inequalities for the log-likelihood ratio expressions dictate the threshold values upon equality, i.e. the LLR threshold is:

$$\ln \eta_1 = \ln \left[\sqrt{\frac{2}{\pi}} \frac{R}{\sigma_c} \right] - \frac{d_1^2}{2\sigma_c^2} \quad (11)$$

for ownship and the LLR threshold for the decoy is:

$$\ln \eta_2 = \ln \left[\sqrt{\frac{2}{\pi}} \frac{R}{\sigma_c} \right] - \frac{(d_2 - D)^2}{2\sigma_c^2} \quad (12)$$

where d_1 is the CPA threshold for ownship, and $(d_2 - D)$ is the CPA threshold for the decoy. For large R , when the CPA threshold is larger than ownship dimensions, equal a priori probabilities can be assumed and the LLR threshold = 0. However, for smaller values of R , and interesting phenomena begins to emerge: a LLR threshold = 0 can lead to a CPA threshold that is smaller than a minimum defined lateral dimension. This lateral dimension is identified with the physical extent of the ship.

The performance enhancement alluded to in the introduction provided a mechanism for dealing with this situation. An *automatically adjusted LLR threshold* can be calculated from the above equations using the minimum defined CPA threshold. This adjustment will result in a negative LLR threshold, which indicates that P_0 is greater than P_1 .

In summary, the proposed method involves the use of CPA predictions, based on sensor measurements, to generate a set of possible hypotheses concerning the outcome of the engagement. A multiple hypothesis test approach is used, incorporating a priori probability assignments concerning the likelihood that the inbound threat is heading for ownship, decoy, or neither. These a priori probabilities, which reflect the observer's information before the engagement occurs, are assumed equal to one another. This assumption in turn leads to a fixed threshold value = 0 for the log-likelihood ratios.

The CPA distance threshold is a function of the LLR threshold as well other parameters such as target range from ownship and sensor accuracy. In general, the CPA distance threshold decreases with range so that at some lower ranges the CPA distance threshold, above which a decision will be made that a threat is not heading for ownship, may be less than a lateral dimension (e.g. length) of ownship. The CPA threshold can be adjusted to give a more realistic decision by changing the LLR threshold.

The following section provides simulation results whose purpose is to quantify the performance of the multiple hypothesis test based upon predicted CPA values. The simulation results also serve to demonstrate the improvement in performance that can be achieved by the application of an adjustable LLR threshold.

3.2.1.5 Simulation Results - Multiple Hypothesis Method

The simulation results presented below are based on two possible engagement trajectories. In the first scenario, the decoy is at a fixed CPA distance from ownship. The threat is initially heading directly for ownship and makes a single dog-leg turn toward the decoy at a range of 10 nmi from ownship (i.e. the threat has been deceived by the decoy). In the second scenario, a moving decoy is launched while the threat is heading for ownship and is deceived by this decoy. The trajectory of the threat after deception is such that the threat is always heading directly towards the decoy as the decoy separates from ownship.

Figures 3-6 and 3-7 show the simulation results with a successful decoy deployed at a distance of 0.25 nmi from ownship. Figure 3-6 reflects a situation where a horizon search radar is used to provide threat trajectory information while Figure 3-7 reflects a situation where an integrated IR tracker is used to complement the horizon search radar. The horizon search radar sensor is assumed to have an update interval of 1 second, a range accuracy of 0.005 nmi and a bearing accuracy of 0.04° . The angular accuracy associated with the IR tracker is assumed to be 0.01° . For both cases an α - β tracking algorithm is assumed with $\alpha = 0.50$ and $\beta = 0.17$.

The inbound missile is assumed to be travelling at Mach 3 (M3) and it makes a 3 g turn at a range of 10 nmi to head for the decoy. Figure 3-6b shows that the CPA hypothesis decision is correct out to a range of approximately 11 nmi except at the range of 5 nmi. The same data was used in Figure 3-6d except that the adjusted LLR threshold method was used. A value of $d_1 = 0.1$ nmi was used in this regard (about 600 feet and somewhat representative of typical ship length) and the associated LLR threshold versus range profile is shown in Figure 3-6c. The same automatic LLR threshold adjustment was used for the fixed decoy chaff cloud (i.e. $\eta_2 = \eta_1$).

Figure 3-6d demonstrates that the "error" at 5 nmi is corrected as result of the application of the LLR threshold adjustment. A lower limit of -1000 was arbitrarily selected for the LLR threshold profile as a function of range.

Significant range-performance improvement can be achieved with the use of a sensor (i.e. the IR tracker) that provides enhanced angular accuracy. More specifically, Figure 3-7b shows that the CPA hypothesis decision is correct out to a range of at least 20 nmi, except for several errors from 5 to 9 nmi, when IR tracker information is used in order to characterize target trajectory. Figure 3-7d shows that all these errors can be corrected by employing the LLR threshold adjustment shown in Figure 3-7c, which was also developed with a minimum CPA threshold of 0.1 nmi.

The same simulation conditions apply to Figures 3-8 and 3-9 except that the inbound missile is not deceived by the fixed decoy and instead heads for the ship in a straight line. Figure 3-8b shows that the CPA decision hypothesis is correct out to a range of about 11 nmi except at 2 and 5 nmi. Figure 3-8d shows that these errors are corrected by employing the LLR threshold adjustment shown in Figure 3-8c. Figure 3-9b shows that the CPA hypothesis decision is correct

out to a range of least 20 nmi, except for one error at 5 nmi, with the enhanced angular measurement accuracy associated with an IR sensor. That error is removed and all decisions are correct out to at least 20 nmi by using the LLR threshold adjustment shown in Figure 3-9c.

Figures 3-10 and 3-11 show simulation results with a successful moving decoy that is launched when the inbound missile is 20 nmi from ownship. Figure 3-10b shows that the CPA hypothesis decision is correct out to a range of approximately 11 nmi except for ranges out to 3 nmi, where the decision is "neither". Figure 3-10d shows that those errors are corrected by employing the LLR threshold adjustment shown in Figure 3-10c. Figure 3-11b shows that the CPA hypothesis decision is correct out to a range of at least 15 nmi with the enhanced angular accuracy of an IR sensor, except for ranges out to 4 nmi, where the decision is "neither". Figure 3-11d shows that those errors are corrected by employing the LLR threshold adjustment shown in Figure 3-11c. However, several errors still occur between 15 and 20 nmi because the moving decoy (having just been launched) is within 0.1 nmi of ownship, and the CPA measurement accuracy is not sufficient to discern that small separation at that range.

3.2.1.6 Conclusion - Multiple Hypothesis Method

Target trajectory changes, as measured by ownship sensors can be extrapolated into the form of predicted CPA values and used, within a multiple hypothesis test framework, to render an assessment of EW effectiveness. The performance of such a technique is directly dependent upon the angular accuracy of ownship sensors. Furthermore, the dynamic adjustment of an LLR threshold can improve performance of this technique in that the physical extent of ownship and decoys are duly accounted for.

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- B. H. L. Van Trees, "Detection, Estimation, and Modulation Theory", John Wiley, Inc., 1968.

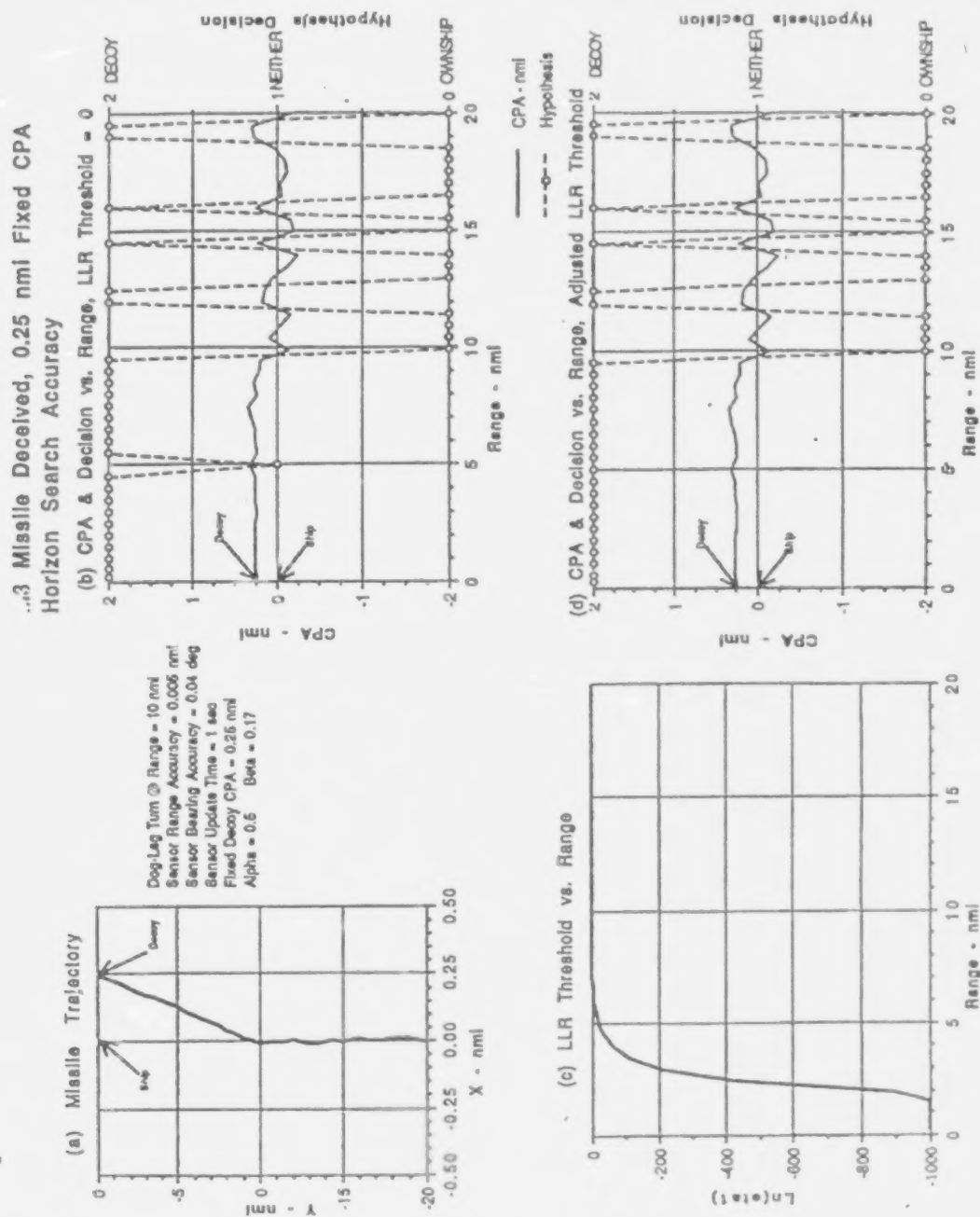
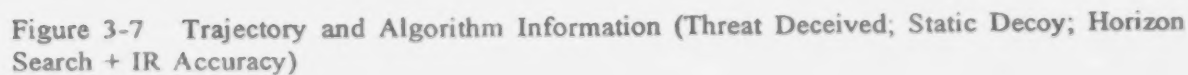


Figure 3-6 Trajectory and Algorithm Information (Threat Detected; Static Decoy; Horizon Search Accuracy)



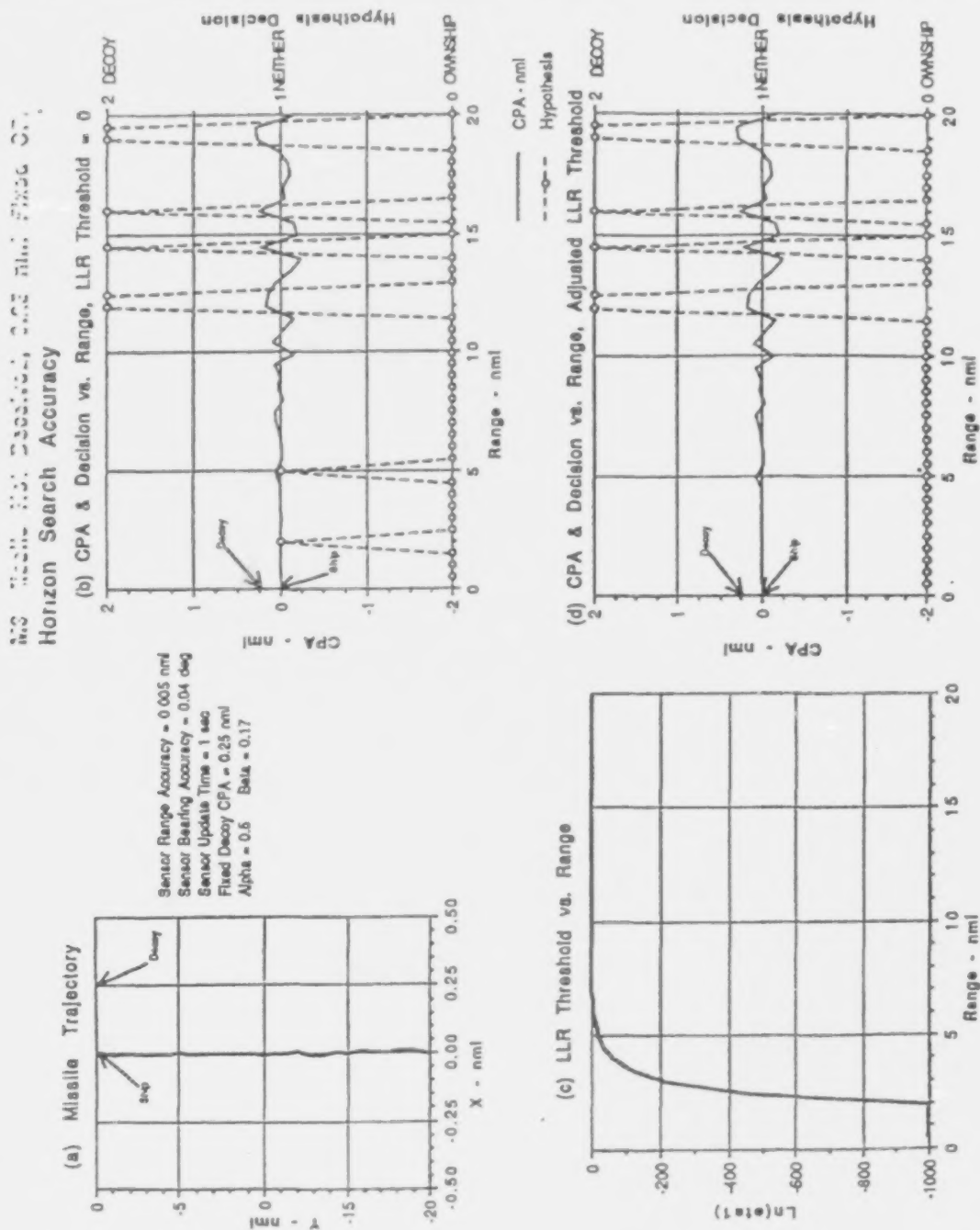


Figure 3-8 Trajectory and Algorithm Information (Threat Not Deceived; Static Decoy; Horizon Search Accuracy)

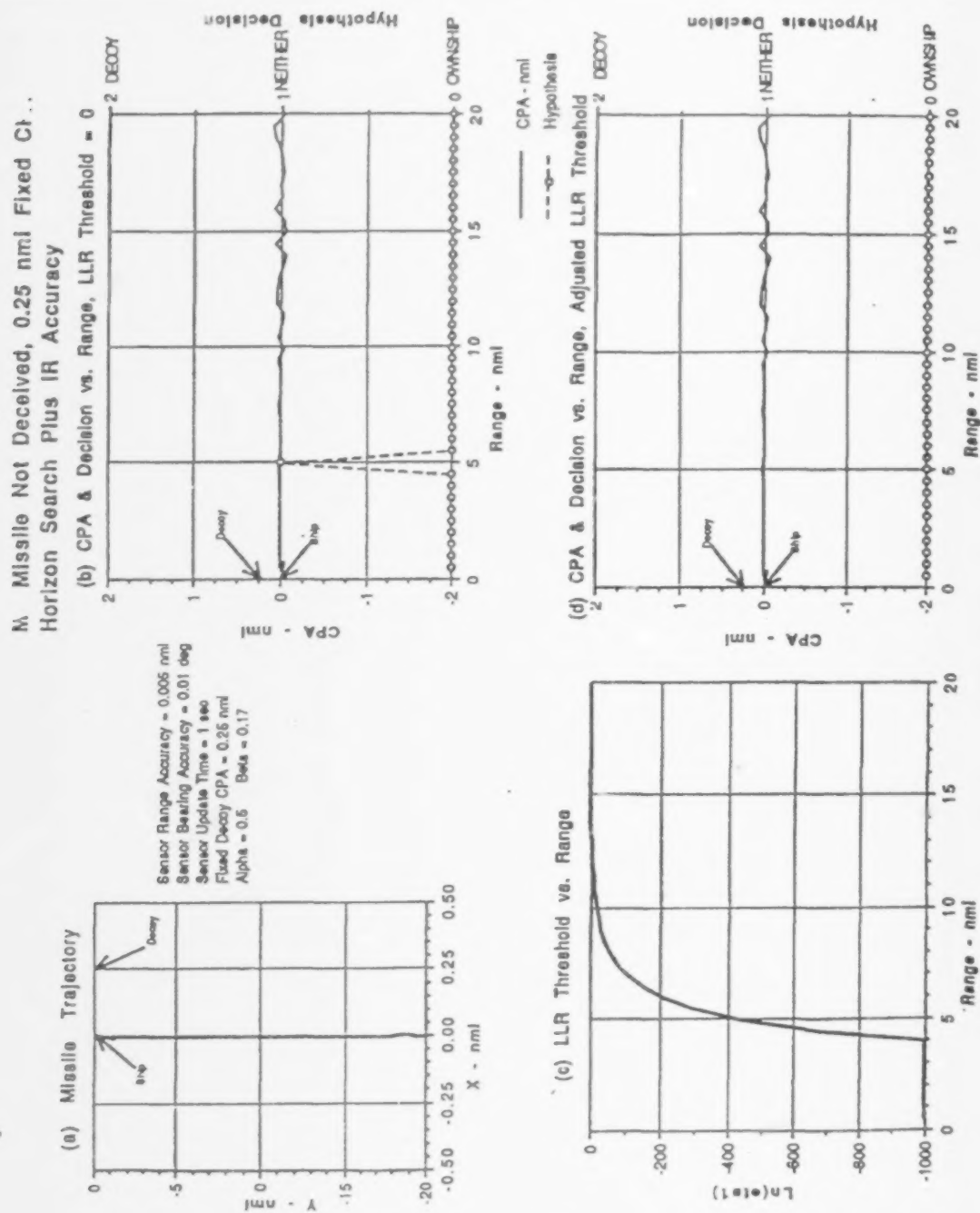


Figure 3-9 Trajectory and Algorithm Information (Threat Not Deceived; Static Decoy; Horizon Search + IR Accuracy)

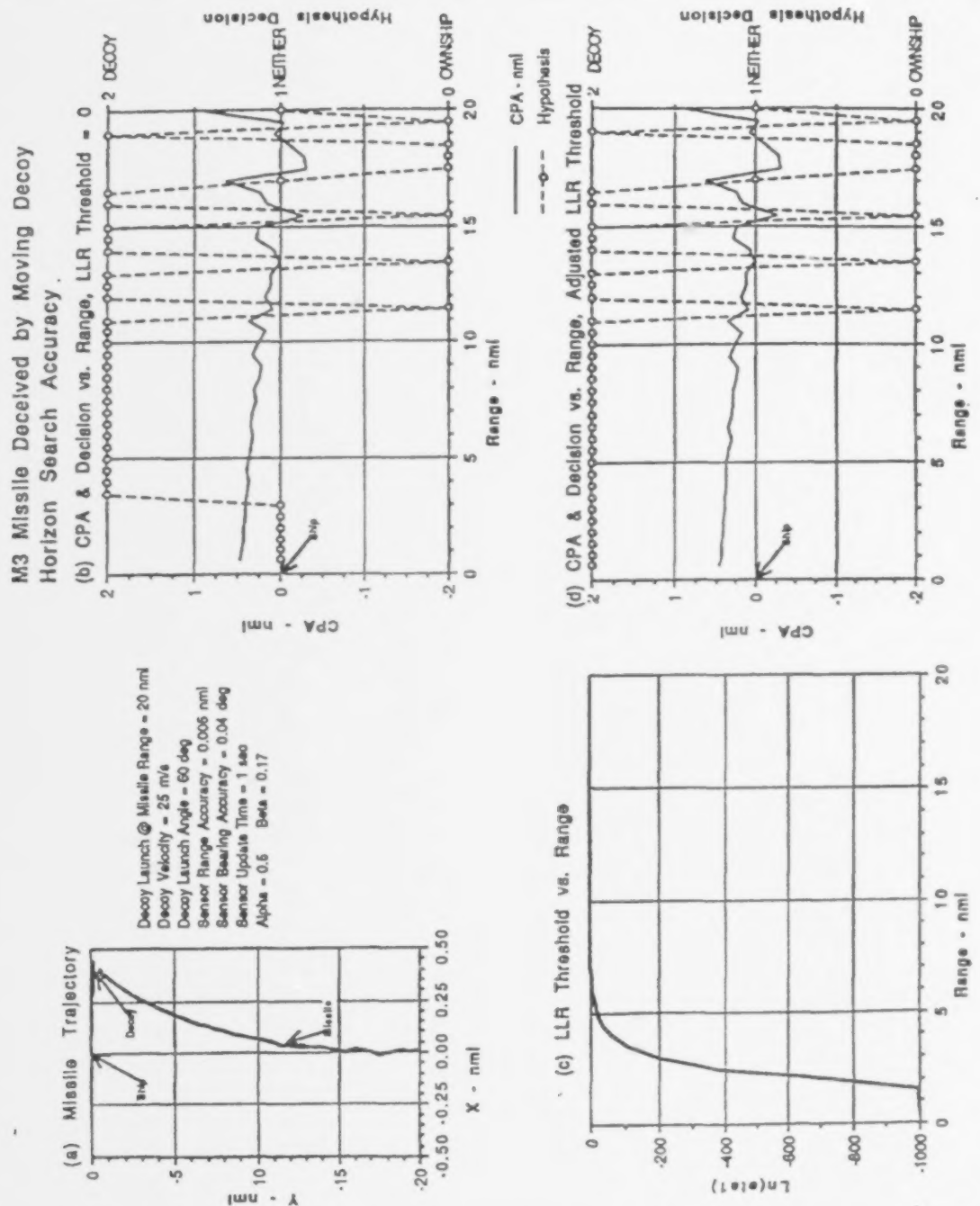


Figure 3-10 Trajectory and Algorithm Information (Threat Deceived; Moving Decoy; Horizon Search Accuracy)

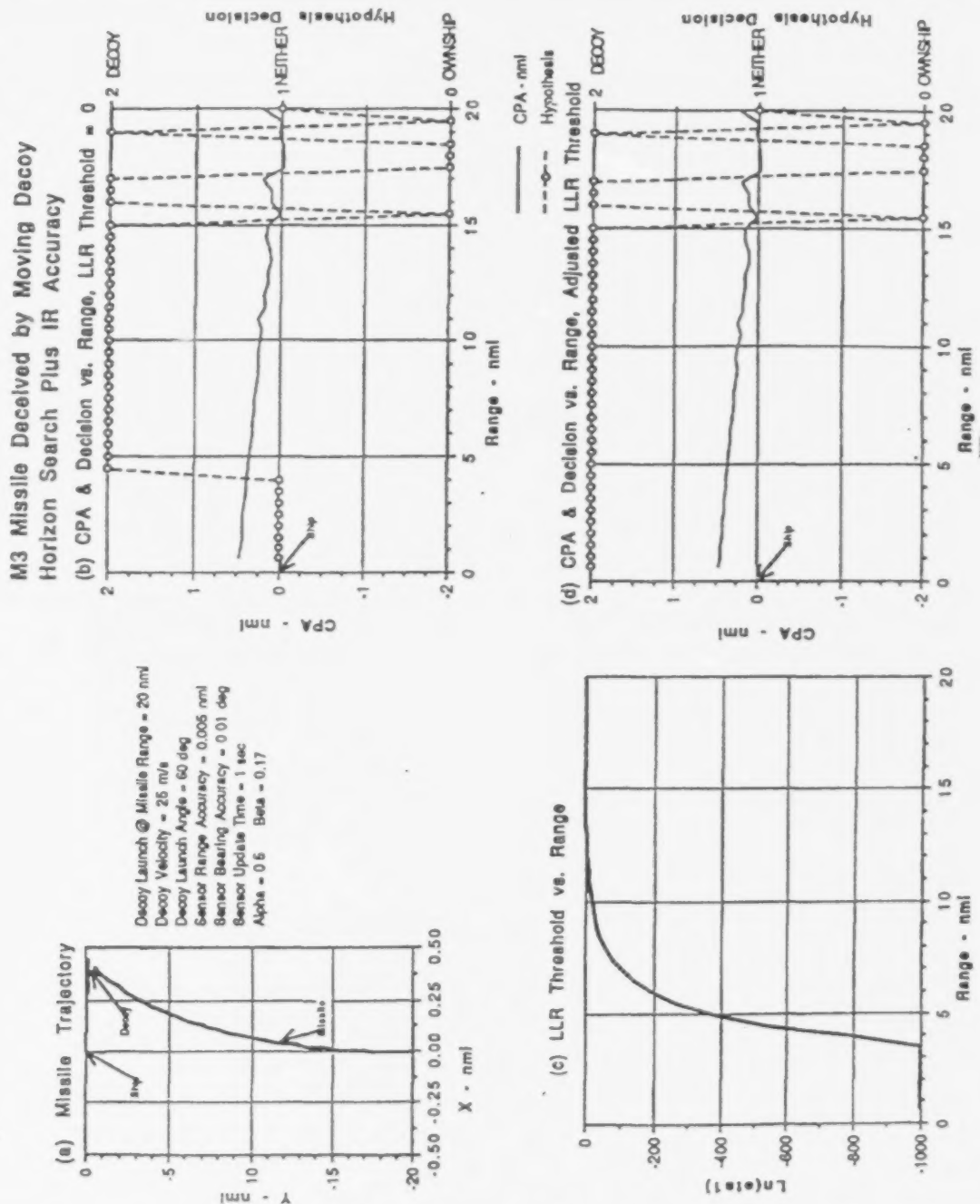


Figure 3-11 Trajectory and Algorithm Information (Threat Deceived; Moving Decoy; Horizon Search + IR Accuracy)

3.2.2 Doppler Changes

3.2.2.1 Introduction

The purpose of this section of the report is to provide visibility into the use of doppler shift measurements in support of ECM effectiveness assessment. More specifically, the detection of a doppler shift in the signal received from an active radar seeker may be indicative of a change in the radial velocity of a missile equipped with such a seeker. Such an event may be construed as evidence that the threat has been successfully decoyed by some ECM tactic.

The following topics will be discussed:

- An overview of the method of using doppler shift measurements to infer changes in direction of motion of the threat;
- An analysis of doppler shift measurements, executed in the context of some relevant tactical scenarios as well as a comparison of ESM performance to radar performance;
- A generalized characterization of the generation of signal samples by an ESM system operating in the presence of noise;
- Establishment of an estimate for emitter doppler shift including the characterization of such an estimate in terms of a variance parameter;
- Examination of the phenomena of outliers, an effect that can become significant for low signal to noise ratios; and
- A brief discussion of some of the practical concerns associated with the use of an ESM system to measure expected emitter doppler shifts.

The material presented in this section is largely, though not exclusively, based on material presented in a paper titled "Estimation of Doppler Frequency in the Presence of Noise", written by Patrick Lie Chin Cheong and published as DREO Technical Note 93-1 (August, 1993).

3.2.2.2 General Discussion of Technique

The measurement of doppler frequency is basically the measurement of the shift in frequency of the received signal. In the case of a radar signal, the doppler frequency shift is related to the radial component of the relative velocity of the target by

$$f_d = - \frac{2\dot{R}f}{c} = - \frac{2\dot{R}}{\lambda} \quad (13)$$

where $\dot{R}$ is the range rate, $\lambda = f/c$ is the transmitted wavelength of the radar signal and f_d is the doppler shift which is taken to be positive for decreasing range R . For a passive intercept receiver such as the Electronic Intelligence (ELINT) or the Electronic Support Measures (ESM) system, the doppler shift is given by

$$f_d = - \frac{\dot{R}}{\lambda} \quad (14)$$

where $\dot{R}$ is the relative radial velocity between the emitter and receiver.

There are many reasons why one would use a passive system such as the ESM receiver instead of an active radar to measure the doppler frequency. Among them, one obvious reason is the unavailability of a radar (such as the STIR) at the required time due to its use in tracking other targets. More importantly, however, the ESM system has the advantage that it can detect an emitting target much earlier than a radar can because the ESM system deals with signals that have experienced a one-way propagation loss whereas the radar deals with signals that have experienced a two-way propagation loss. Thus, information about a change in the target's trajectory can be rendered much sooner using an ESM system.

Another advantage associated with the use of an ESM receiver is that, unlike a radar, it will not provide a beacon for threats to home on. In this respect, it is to be noted that certain threats can passively home on radar emissions of their targets.

The ESM receiver measures the frequency of a received signal and has no knowledge of the transmitted frequency. Therefore, it is not possible to calculate the shift in frequency due to the relative target motion between the emitter and the receiver. However, the ESM system can determine **changes** in target radial velocity. This can be useful in for the detection of a change in the trajectory of an active emitter. As an example, suppose that the velocity of a target emitter (missile) is V_i m/s and is travelling directly towards the receiver (ship A) as shown in Figure 3-12. At some point along the route, it changes trajectory and turns Φ° away from the ship. The change in radial velocity due to the change of Φ° from the original trajectory is given by

$$\Delta V_{rel} = V_i - V_i \cos \Phi = V_i (1 - \cos \Phi) \quad (15)$$

Hence the shift in frequency of the signal at the receiver is:

$$f_d = - \frac{V_i (1 - \cos \Phi)}{\lambda} \quad (16)$$

For $\Phi = 5^\circ$, $\lambda = 0.03$ m, and $V_i = 300$ m/s, the doppler frequency shift f_d is then equal to 38.05

Hz. We can rewrite equation (4), solving for Φ as:

$$\Phi = \cos^{-1} \left(1 - \frac{f_d \lambda}{V_i} \right) \quad (17)$$

where f_d is the shift in frequency and $f_d \geq 0$. Assume that we are able to estimate f_d down to, for example, 10 Hz. Assuming the values for V_i and λ , this means that we will be able to detect changes in threat trajectory that exceed $\approx 2.6^\circ$.

3.2.2.3 Representative Scenarios

Now we will discuss the advantage of using an ESM system with the capability of measuring doppler frequency with an accuracy of 10 Hz or less compared to a monopulse radar that has an angular resolution of 0.3° . Three different representative tactical situations will be described and these two methods for detecting threat trajectory changes will be compared.

Referring to Figure 3-12, consider the first scenario where the missile has locked onto the ship A and the latter is trying to transfer the lock from itself onto the nearby chaff cloud through the use of some electronic countermeasures. The chaff was released by the ship in an attempt to seduce the missile and as such, is not very far from the ship. In this scenario, it is assumed that the distance (d) between the chaff cloud and ship A is approximately 300 m. To simplify the example, assume that the ship and the chaff cloud form a line that is perpendicular to the initial missile trajectory. It has been shown (above) that for a receiver that can measure a shift in frequency down to 10 Hz, a change in trajectory as low as 2.6° can be detected for $V_i = 300$ m/s and $\lambda = 0.03$ m. This implies (Figure 3-12) that the receiver will be able to detect any deviation of the missile onto the chaff within the range $R_{esm} = d/\tan\Phi = 0.3/\tan(2.6^\circ) \approx 6.7$ km.

For a monopulse radar system with angular resolution of β° , the maximum range R for which a change of trajectory of Φ° can be detected in a time of t_r seconds or less is:

$$R = \frac{t_r V_i \sin\Phi}{\tan\beta} = \frac{t_r V_i \sin\Phi}{\beta} \quad (18)$$

where for small values of β , $\tan\beta \approx \beta$. As can be seen from the above expression, the range R is proportional to the required response time t_r and the velocity V_i of the target, but inversely proportional to the angular resolution. A plot of range (R) versus the response time (t_r) for different velocities (V_i) is shown in Figure 3-13 with the trajectory change of $\Phi = 5^\circ$ and an angular resolution of $\beta = 0.3^\circ$. In the first scenario as described above, the deviation angle Φ must satisfy the equation $\tan\Phi = d/(R + t_r V_i \cos\Phi)$. Solving this equation simultaneously with (6) yields the maximum range $R_{radar} \approx 5.1$ km for $V_i = 300$ m/s, $t_r = 2$ s, $\beta = 0.3^\circ$, and $d = 300$ m.

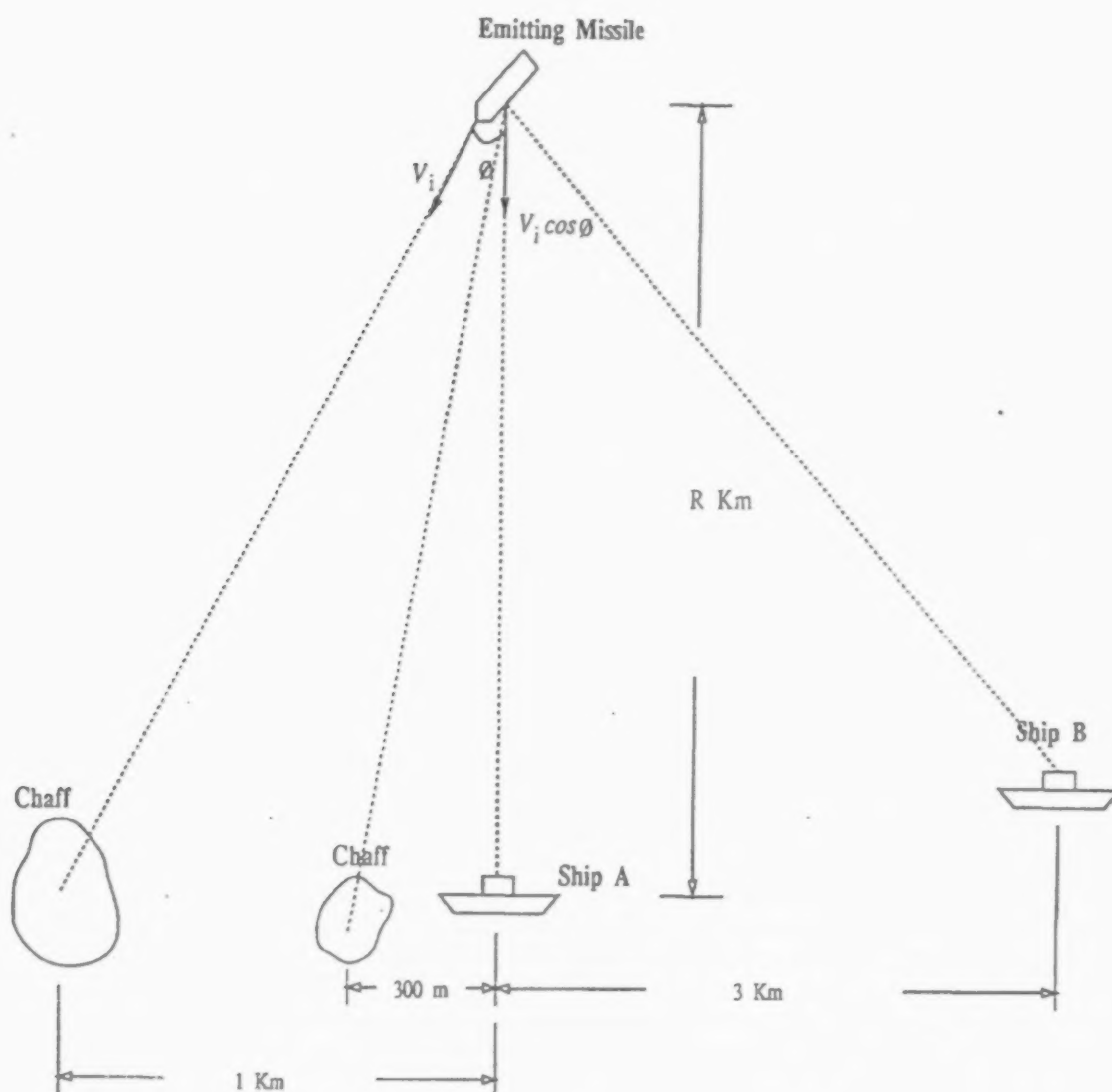


Figure: 3-12 Change in Trajectory of Target Emitter

Consider now a second scenario where chaff is deployed in order to counter the acquisition mode of the threat seeker. That is, the chaff is deployed prior to missile seeker acquisition of the ship. Under such a tactic the chaff is deployed further from the ship than in the first scenario (seduction tactic). Under the second scenario, the distance d between the chaff and the ship is taken to be approximately 1 km as indicated in Figure 3-12. Using this value of d and with the other variables having the same value as before, the maximum range R_{esm} for which the doppler ESM receiver can detect a change in trajectory is ≈ 22.4 km. Note that R_{esm} is proportional to the distance d between the ship and the chaff. For the monopulse radar with the same angular resolution of 0.3° and maximum response time of 2 seconds, by solving the previous equations, the maximum range R_{radar} obtained is ≈ 10.4 km.

Similarly, consider a third scenario where the missile deviates to track ship B instead of ship A, the doppler receiver can detect this change well beyond the horizon. If the distance d between ship A and B is approximately 3 km, and with all the other variables remaining the same, we obtain $R_{esm} \approx 67.1$ km and $R_{radar} \approx 18.1$ km. The results for each of the three scenarios are summarized in Table 3-4.

TABLE 3-4 Doppler and radar measurements

Scenarios	ESM Receiver with Doppler measurement accuracy = 10 Hz	Radar with angular resolution = 0.3° & maximum response time = 2 seconds
$d = 300$ m	$R_{esm} = 6.7$ km	$R_{radar} = 6.0$ km
$d = 1000$ m	$R_{esm} = 22.4$ km	$R_{radar} = 10.4$ km
$d = 3000$ m	$R_{esm} = 67.1$ km	$R_{radar} = 18.1$ km

Having addressed the tactical relevance of doppler shift measurements to the domain of ECM effectiveness assessment, we now turn to the subject of specific methods for estimating the doppler shift associated with a signal that is corrupted by noise. In particular, the remainder of this report sub-section will address methods for establishing and characterizing the best possible doppler shift estimate that can be attained under specific conditions and assumptions. The maximum likelihood estimate (MLE) technique for computing doppler shift will be explored. In order to properly characterize this estimate, methods for determining the lower bound of the variance associated with the MLE will also be discussed.

3.2.2.4 Characterization of Received Signal in Presence of Noise

The problem domain of interest involves the determination of signal frequency in the presence of noise. More specifically, the received signal is assumed to be of the form $x(t) = a(t)\cos(\hat{\omega}_d t + \Theta)$, where the amplitude $a(t)$, the phase Θ , and the angular frequency $\hat{\omega}_d$ are all assumed to be

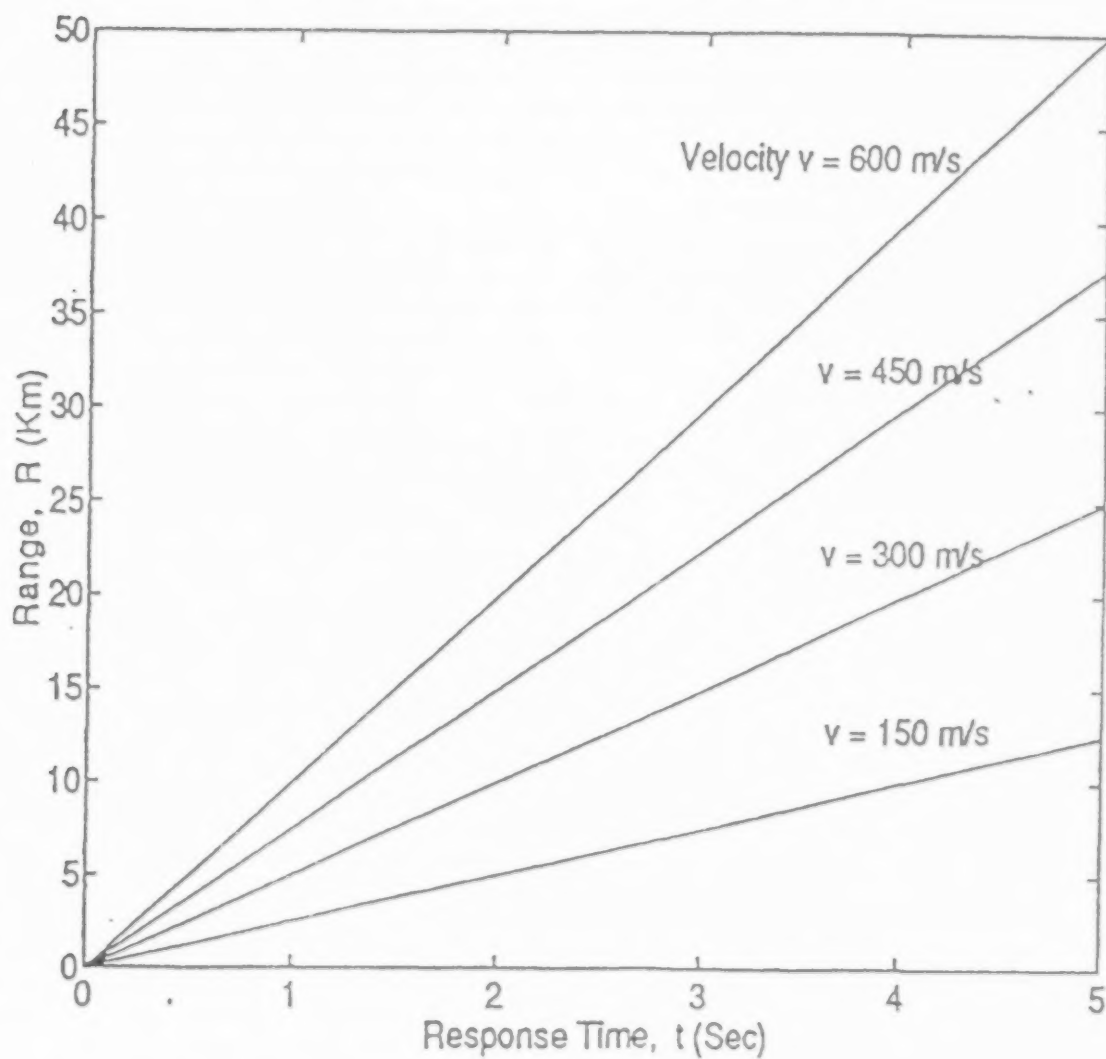


Figure: 3-13 Range vs Response Time (Trajectory Deviation = 5° , Angular Resolution = 0.3°)

unknown. In addition, it is assumed that the incoming RF signal is coherent. Furthermore, it is assumed that a finite number of discrete samples of the received signal are available for processing.

Expressions for the sampled signals which serve as the input to the process of deriving estimators (e.g. doppler frequency estimate and associated variance) will now be given. The incoming signal is assumed to be any coherent signal whose carrier is modulated by a waveform $a(t)$. It is further assumed that the initial carrier frequency ω_c has already been obtained and is known (Note that ω_c is not the transmitted frequency). Suppose that there is a shift in frequency of the signal due to the doppler effect. The incoming signal is then given by:

$$x(t) = a(t) \cos[(\omega_c + \omega_d)t + \theta_0] + n(t) \quad (19)$$

where $\omega_d = 2\pi f_d$ is the doppler shift and $n(t)$ is additive white noise with mean = 0 and variance = σ^2 . Assuming that $x(t)$ is applied to an in-phase and quadrature (I/Q) demodulator, the noise $n(t)$ can be represented in terms of in-phase and quadrature components $n_c(t)$ and $n_s(t)$, respectively, where $n_c(t)$ and $n_s(t)$ are also Gaussian with zero mean and variance σ^2 , that is:

$$n(t) = n_c(t) \cos(\omega_c t) - n_s(t) \sin(\omega_c t) \quad (20)$$

The demodulated in-phase and quadrature baseband signals $I(t)$ and $Q(t)$ are then given by:

$$I(t) = a(t) \cos(\omega_d t + \theta_0) + n_c(t) \quad (21)$$

$$Q(t) = a(t) \sin(\omega_d t + \theta_0) + n_s(t) \quad (22)$$

The baseband signals are then sampled at a rate of $f_s = 1/T_s$ per second. The sampled signals then obtained are equal to:

$$I_k = a_k \cos(\omega_d f_k + \theta_0) + n_c \quad (23)$$

$$Q_k = a_k \sin(\omega_d f_k + \theta_0) + n_s \quad (24)$$

where $t_k = t_0 + kT_s$, for $k=0, 1, 2, \dots$, and I_k, Q_k, a_k, n_c , and n_s are defined as $I(t_k), Q(t_k), a(t_k), n_c(t_k)$, and $n_s(t_k)$ respectively. The noise samples n_c and n_s are statistically independent Gaussian variables with mean = 0 and variance = σ^2 .

3.2.2.5 Variance Bounds on Parameter Estimation

As alluded to earlier, there are limits to the degree of accuracy with which doppler shift can be measured for a signal characterized by a finite number of samples measured in the presence of noise. More specifically, there is a lower limit on the variance that is achievable when attempting to estimate signal doppler frequency. The value of this lower bound on variance is determined by the Cramer-Rao method. It is found that the value of the Cramer-Rao bound is inversely proportional to the Signal to Noise Ratio (SNR), inversely proportional to the square of the sampling time interval (T_s), and inversely proportional to the cube of the number of signal samples obtained (N).

Now consider that we have N sample values of I_k and Q_k , i.e. $k=0, 1, 2, 3, \dots, N-1$. From these values of I_k and Q_k , we can form the N sampled complex envelope $Z_k = I_k + jQ_k$, where $j = \sqrt{-1}$.

Due to the fact that the received signal is corrupted by noise and is, therefore, random in nature, we can only obtain estimations of the signal parameters. Furthermore, since the values of the estimates are dependant on the observation data, they are also random variables and as such have a mean and a variance. An *unbiased* estimator is one whose mean value is equal to the true value of the parameter and a *minimum-variance* estimator is one whose variance is less than or equal to the variance of any other estimator. The minimum-variance unbiased estimator is unique, but it may not always exist. Under certain conditions, it can be shown that the variance of any unbiased estimator cannot be less than a particular lower bound known as the Cramer-Rao bound.

A derivation of the Cramer-Rao bound for the problem at hand yields the following:

$$\text{Var}(\hat{\omega}) = \sigma_{\hat{\omega}}^2 \geq \frac{12\sigma^2}{a^2 T_s^2 N(N^2 - 1)} \quad (25)$$

where:

$\hat{\omega}$ = estimate of the true value of ω ;
 σ^2 = variance of signal samples in presence of noise;
 a = amplitude of received signal;
 T_s = sampling time interval;
 N = number of signal samples.

In terms of the signal-to-noise ratio which is defined as $SNR = \alpha^2/(2\sigma^2)$, the Cramer-Rao bound for the variance of the frequency estimate is $\sigma_{\hat{\omega}}^2 \geq 6f_s^2/[(SNR)N(N^2-1)]$ where $f_s = 1/T_s$ is the sampling rate.

3.2.2.6 Maximum Likelihood Estimation

Having determined the lower bounds for the mean-square error associated with the doppler shift estimate, attention is now directed to the derivation of the estimate itself using the maximum-likelihood (ML) method. The ML estimator maximizes the probability density function $p(Z; \Omega)$ with respect to the vector Ω where the elements of Ω are the parameters to be estimated and Z is the observed sample data. In this case, our interest is limited to an estimate for the doppler frequency $\hat{\omega}_d$; however, it is also possible to derive estimates for other parameters of the received signal $x(t)$ (refer to equation (7)) such as a and Θ_s .

Application of the ML method yields the following as an estimate for the doppler frequency:

$$\hat{\omega}_d = \max |A(\omega)| \quad (26)$$

where:

$$A(\omega) = \frac{1}{N} \sum_{k=0}^{N-1} Z_k e^{-jk\omega T_s} \quad (27)$$

3.2.2.7 Relationship with the Discrete Fourier Transform

From the definition of the discrete Fourier transform of the sampled complex envelope $\{Z_k\}$, and normalized by the number of points N , we have

$$A_l = \frac{1}{N} \sum_{k=0}^{N-1} Z_k e^{-j \frac{2\pi k l}{N}} \quad \text{for } l=0, 2, \dots, N-1. \quad (28)$$

Thus, from the expression of $A(\omega)$ in (15), it can be seen that

$$A_l = A\left(\frac{2\pi l}{NT_s}\right) = A\left(\frac{\omega_s l}{N}\right) \quad \text{for } l=0, 2, \dots, N-1 \quad (29)$$

where $\omega_s = 2\pi/T_s = 2\pi f_s$. The values of A_l , therefore, represent the sampling points of the continuous spectrum $A(\omega)$, with the sampling intervals equal to ω_s/N . Note that $A(\omega)$ repeats itself at every ω_s interval, that is, $A(\omega)$ is periodic with period ω_s . In addition, if we have an a priori knowledge about the range or the maximum value of the frequency to be estimated (ω_d), we can reduce the search space by choosing a sampling rate ω_s close to the largest possible value of ω_d .

Figures 3-14 and 3-15 show the spectra of $|A(f)|$ ($f = \omega/2\pi$), with $N = 64$, $f_d = 500$ Hz, $f_s = 10$ kHz, and $SNR = 0$ dB in Figure 3-14 and $N = 32$, $f_d = 500$ Hz, $f_s = 10$ kHz, and $SNR = 20$ dB in Figure 3-15. The crosses along the curves of the figures represent the magnitudes of the N points DFT of $A(f)$, that is the $\{|A_l|\}$ points, $l = 0, 1, \dots, N-1$. The value of f at which the maximum point of $|A(f)|$ occurs is the ML estimation of f_d , i.e., $\hat{f}_d$, and the value of $|A(f)|$ at that point is the ML estimation of a_0 , i.e., $\hat{a}_0$. In the case of Figure 3-14, the values of $\hat{f}_d$ and $\hat{a}_0$ obtained are $\hat{f}_d = 507.23$ Hz and $\hat{a}_0 = 0.961$, whereas those of Figure 3-15, $\hat{f}_d = 499.27$ Hz and $\hat{a}_0 = 0.985$. From the N DFT points in Figure 3-14, the maximum is $|A_4|$ which has a value of 0.86 and which is at 486.75 Hz and in Figure 3-15, the maximum is $|A_3|$ with a value of 0.75 and at 625 Hz.

Comparing the two plots, it can be observed that having a larger value of N causes the width of the peaks (lobes) in the spectrum to become smaller, that is, the width is inversely proportional to NT_s . As the signal-to-noise ratio increases, the sidelobes' peaks decrease and the values of $\hat{f}_d$ and $\hat{a}_0$ approach the exact values as expected. It is to be noted that if no noise is present, $|A(\omega)|$ will be a sinc function which is symmetric about the doppler frequency ω_d and which has a period of ω_s . The global maximum point will then occur at exactly ω_d and will have an exact amplitude of a_0 . In the presence of noise, however, the sinc function of $|A(\omega)|$ is distorted with the sidelobes' peak values becoming larger and the global maximum point being shifted away from the true value of ω_d . The difference between the maximum DFT point to the true maximum of $|A(\omega)|$ depends on M , the number of DFT points used in the computation, but is independent of the SNR. The larger the value of M , the more accurate is the DFT approximation.

While the Cramer-Rao bound provides the mean-square error of the ML estimate for large SNR, other considerations apply in the case of low SNRs. As the SNR decreases, the probability increases of the occurrence of an outlying frequency component whose magnitude is the largest. An outlier is defined as that frequency component which is not in the main lobe containing the transmitted signal frequency but which has a magnitude larger than the main lobe. When the maximum peak frequency component (outlier) occurs far removed from the exact frequency ω_d , severe errors occur in the ML frequency estimate.

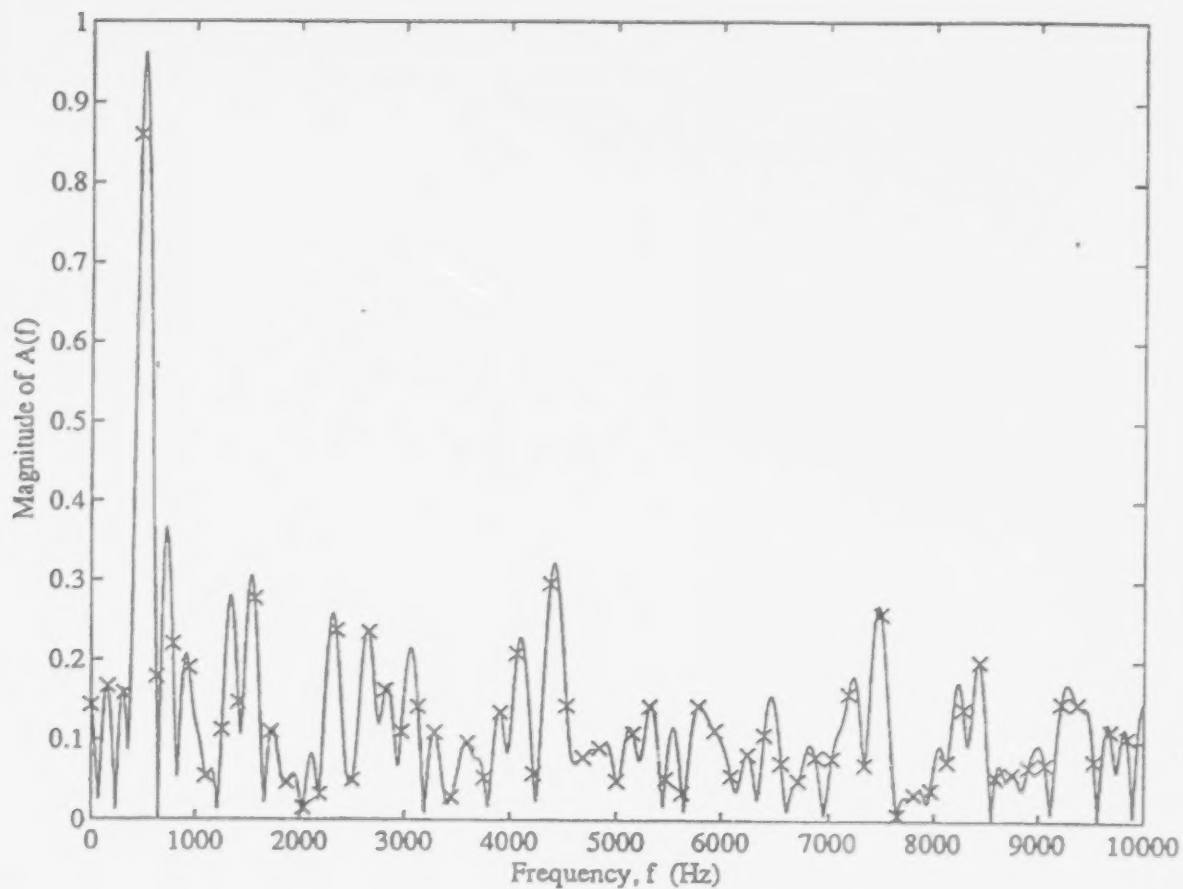


Figure: 3-14 Spectrum of $\text{Mag}(A(f))$ ($N=64$, $f_d=500$ Hz, $f_s=10$ KHz, $\text{SNR}=0$ dB)

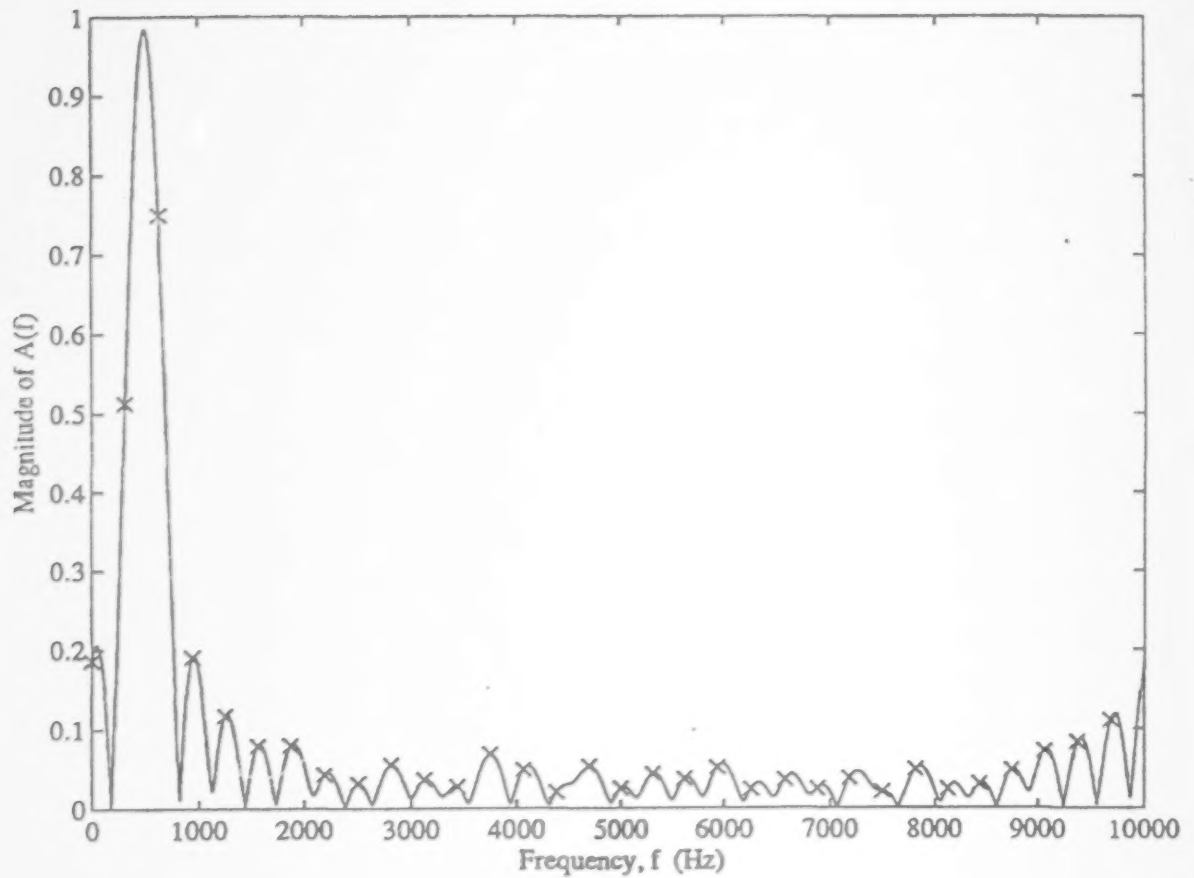


Figure: 3-15 Spectrum of $\text{Mag}(A(f))$ ($N=32$, $f_d=500$ Hz, $f_s=10$ KHz, $\text{SNR}=20$ dB)

3.2.2.8 Threshold Effects Due to the Occurrence of Outliers

For simplicity of analysis, it will be assumed that an outlier can occur anywhere between 0 and ω_s (sampling frequency). That is, the probability density function is approximately uniform. In this case, the variance or the MSE due to an outlier is $\omega_s^2/12$. The MSE of the ML estimate for any value of SNR is, therefore, given by:

$$\text{MSE} = P(\text{outlier}) * (\text{MSE due to outlier}) + P(\text{no outlier}) * (\text{MSE due to no outlier})$$

$$= q \cdot \frac{\omega_s^2}{12} + (1 - q) \cdot \frac{3\omega_s^2}{2\pi^2(\text{SNR}) N(N^2 - 1)} \quad (30)$$

where q is the probability of an outlier and in the absence of any outlier, the MSE is taken from the Cramer-Rao bound. The outlier probability q is a complex function of SNR and the number of signal samples taken (N). A plot of q versus SNR for different values of N are shown in Figure 3-16. With these values of q , the mean square error of the maximum-likelihood frequency estimation given by (18) can be calculated. The root mean square (RMS) error of the ML estimation is then obtained by taking the square root of the MSE.

The RMS frequency errors are plotted against the input SNR for different values of N in Figures 3-17 and 3-18, where the sampling rate $f_s = \omega_s/(2\pi)$ are 10 kHz and 100 kHz, respectively. As can be seen from these plots, depending on the values of N and f_s , the threshold effect takes place somewhere below 0 dB. The straight lines in the graphs represent approximately the Cramer-Rao bounds. For a given value of N , SNR, and f_s , it can easily be determined if the ML estimation is being operated above or below the threshold effect by direct inspection of the plots provided in Figures 3-17 and 3-18.

3.2.2.9 Determination of the Maximum-Likelihood Frequency Estimate

The task of determining the actual estimate of a doppler frequency remains unresolved; equation (14) expresses the estimate in terms of maximizing the function $A(w)$. To be more specific, the ML frequency estimation of the signal is the angular frequency that maximizes the magnitude of $A(\omega)$. In order to determine the ML frequency estimate, an approach consisting of a coarse search followed by a fine search is recommended. The coarse search yields a rough estimate of where the global maximum of the spectrum is located; this is achieved through the application of the fast Fourier transform algorithm. The fine search uses the coarse estimate as the initial guess in order to give a more accurate result for frequency estimation ω_{max} .

Central to this technique is the computation of an M -point ($M \geq N$) Discrete Fourier Transform of the complex data $\{Z_k\}$, $k=0,1,2,\dots,N-1$, where $\{Z_k\}$ is a complex representation of the in-phase and quadrature components of the received signal.

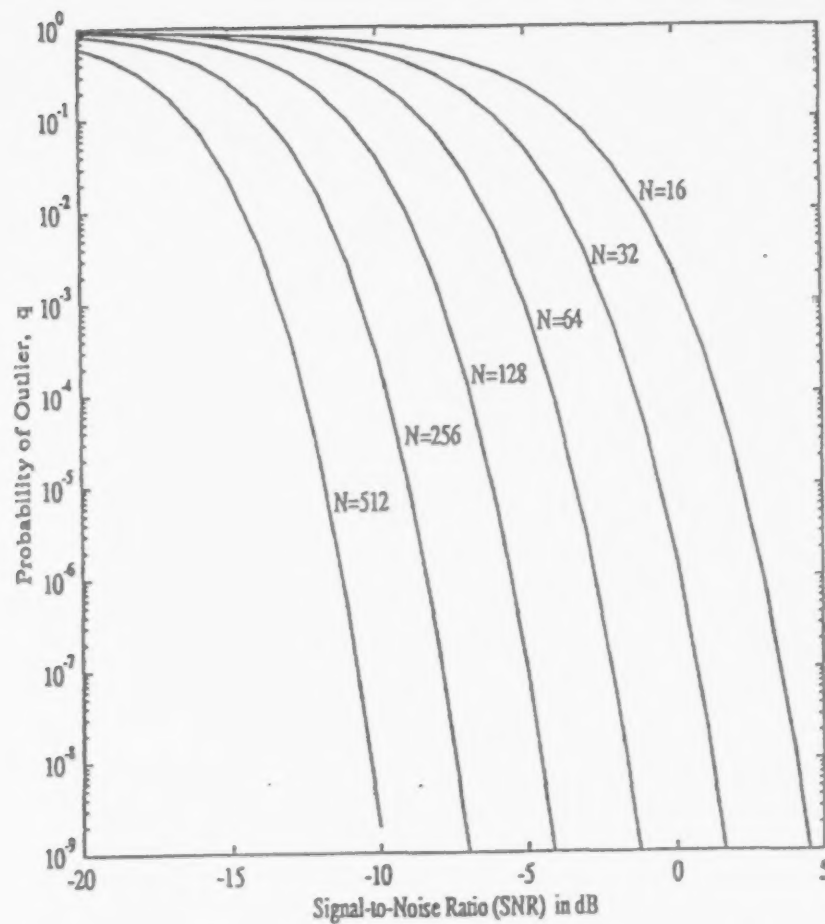


Figure: 3-16 Probability of Outlier, q , vs SNR for Various Values of N

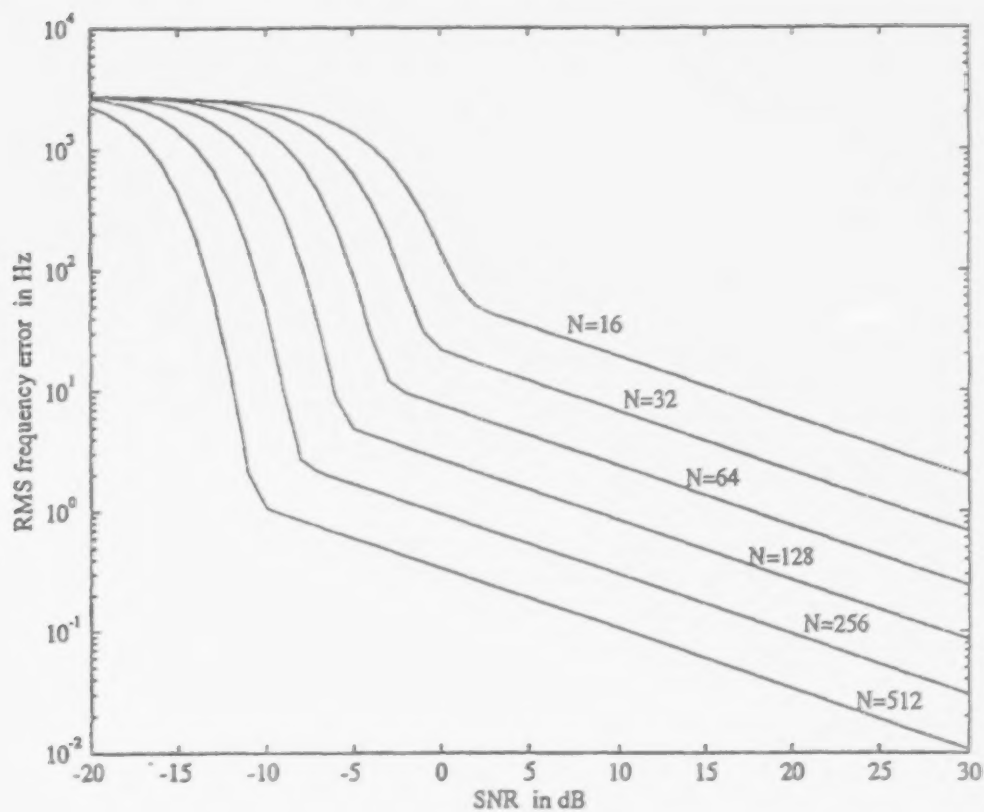


Figure 3-17 RMS Error of ML Frequency Estimate vs SNR, $f_c=10$ KHz

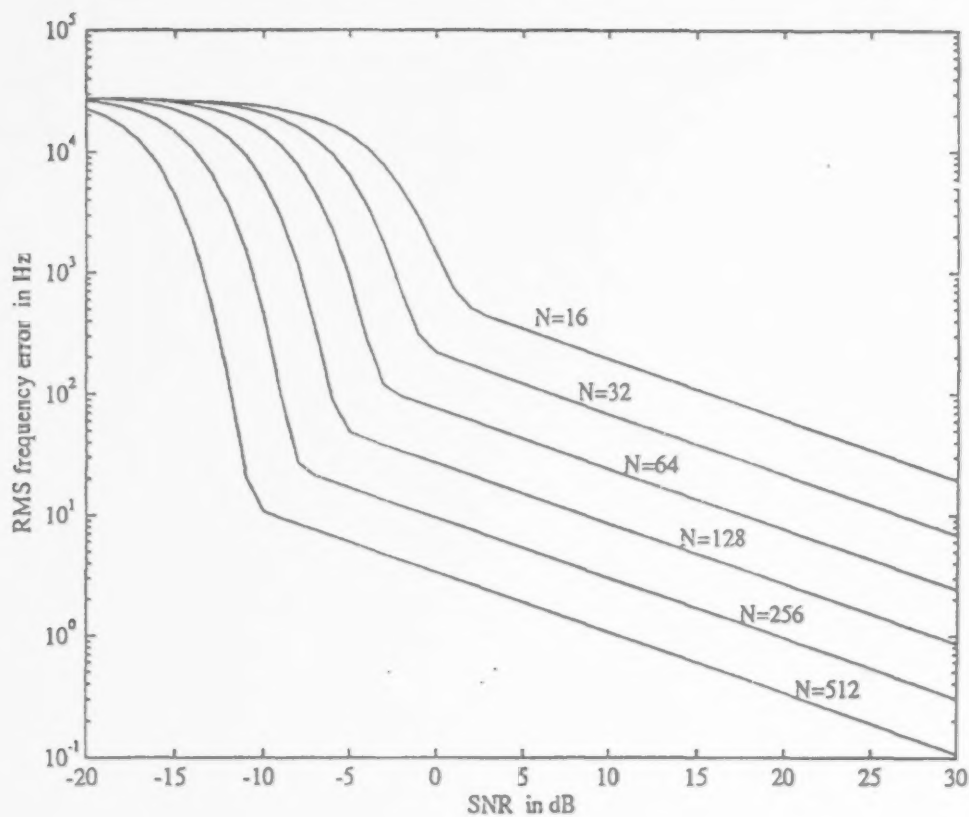


Figure 3-18 RMS Error of ML Frequency Estimate vs SNR, $f_s=100$ KHz

An approximate value for $\hat{\omega}_{max}$ can be assumed to lie anywhere between l_{max} and its neighbouring DFT point. Note that $l_{max} = \max [\text{mag}(A_l)]$, $l = 0, 1, 2, \dots, M-1$ and A_l represents the sampling points of the continuous spectrum $A(\omega)$ (determined via DFT) with the sampling interval $= \omega_s/M$. It is implied that the $\hat{\omega}_{max}$ is a random variable that is uniformly distributed in the interval of ω_s/M . Hence, the MSE associated with the approximation of $\hat{\omega}_{max}$ by $l_{max} \omega_s/M$ is equal to $\omega_s^2/(12M^2)$. The overall mean-square error τ^2 in determining the signal or doppler frequency $\hat{\omega}_d$ is, therefore, equal to the variance of the ML estimation of $\hat{\omega}_d$ in the presence of noise as given by (18) plus the variance of approximating $\hat{\omega}_{max}$ by the maximum magnitude DFT point. That is:

$$\epsilon^2 = q \frac{\omega_s^2}{12} + (1 - q) \frac{3\omega_s^2}{2\pi^2(\text{SNR})N(N^2 - 1)} + \frac{\omega_s^2}{12M^2} \quad (31)$$

with $M = mN$, and $m > 1$. For moderate to high signal to noise ratio, the variance of the ML estimation can be approximated by the Cramer-Rao bound and the overall MSE ϵ^2 can be determined from:

$$\epsilon^2 \approx \frac{3\omega_s^2}{2\pi^2(\text{SNR})N(N^2 - 1)} + \frac{\omega_s^2}{12m^2N^2} \quad (32)$$

The overall root-mean-square error ϵ is then obtained by taking the square root of ϵ^2 . Depending on the values of m and N used, it is seen from the above expression (20) that the MSE due to use of the maximum magnitude DFT point as an approximation to the signal's frequency (second term) can be much larger than the inherent MSE of the ML frequency estimation (first term).

At a low SNR, however, the dominant error component is due to the occurrence of outliers given by the first term of equation (19). The overall RMS error τ is shown in Figure 3-19 as a function of SNR with the sampling rate $f_s = 10 \text{ kHz}$ and the value of m equal to 8. Comparing Figures 3-17 and 3-19, the effect due to the MSE of the DFT approximation can be easily observed. As stated earlier, this error increasingly becomes the dominant factor as the SNR increases. This is because the variance of the ML estimation given by the Cramer-Rao bound is inversely proportional to the SNR, whereas the DFT approximation error is independent of SNR. Hence, with increasing values of SNR, the MSE of the ML estimation becomes negligible compared to the MSE of the DFT approximation which remains basically constant for a given value of m and N .

3.2.2.10 Practical Considerations

The use of doppler shift measurements in order to identify changes in threat trajectory, while possible in principle, presents some significant technical challenges. The particular challenge is to achieve the capability of measuring doppler shifts that are on the order of tens of Hz. Current ESM systems generally have relatively wide IF bandwidths in order to maximize the amount of

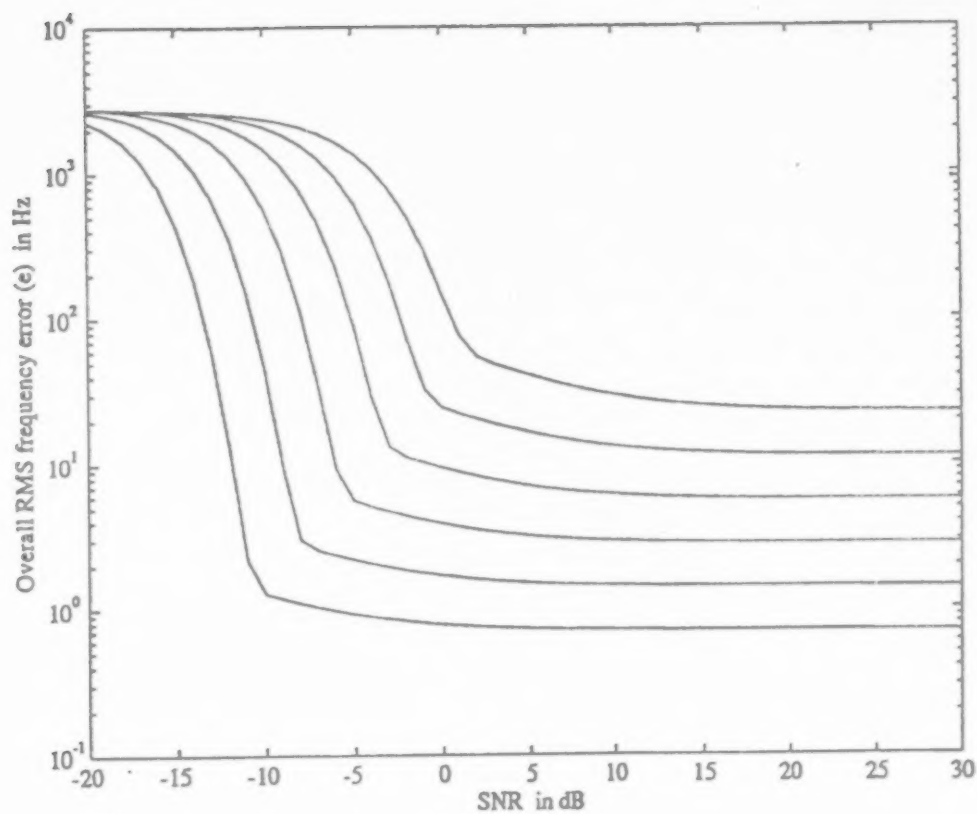


Figure 3-19 Overall RMS Frequency Error vs SNR and N with $f_s = 10$ KHz, $m=8$

emitter energy received and thus maximize the probability of detection. Such systems would be incapable of providing the required accuracy in frequency measurement.

An ESM system that would support the use of doppler shift measurements for ESM effectiveness assessment would require a specialized narrowband receiver. Such a receiver would likely need to be "cued" by another ESM system in order to search the proper portion of the spectrum for the emitter signal. The achievement of the necessary frequency measurement accuracy will be difficult for a variety of reasons including the presence of instabilities in both the source emitter as well as the receiver. The achievement of measurement accuracies of less than 1000 Hz is a demanding requirement that might possibly be addressed through the implementation of extra delay lines to narrow the ESM system's response characteristics. It is understood that Raytheon has used low doppler shift measurements within the context of a triangulation procedure used to determine approximate emitter range with an ESM system. Information about this application would be helpful.

An environmental factor that complicates the use of doppler shift measurements for effectiveness assessment is the presence of the multipath effect. Of particular relevance to low altitude targets, the multipath effect gives rise to the phenomena of doppler spreading whereby the motion of sea waves confers an additional doppler shift upon signals that are incident upon the ESM antenna. It remains to be determined if the doppler shift contribution associated with this effect masks the doppler shifts of interest: those associated with a change in the apparent radial velocity of the target.

3.2.3 IR Signature Changes

3.2.3.1 Introduction

This study has been performed to assess the feasibility of using infrared (IR) measurements to detect trajectory deviations in anti-ship missiles. The rationale behind this is as follows. Virtually all softkill techniques, when successful, cause the threat to change trajectory. If it can be shown that the amount of IR power radiated by the threat is a function of its viewing aspect, and if such changes could be accurately detected and measured, as well as isolated from other effects which cause changes in the IR signature of the threat, then such changes could be used to determine whether a threat has been successfully prosecuted by softkill.

The material presented in this section covers the following topics:

- Discussion of IR sensors;
- Definition of representative threat attributes;
- Discussion of factors affecting threat radiant intensity; and
- Conclusion.

3.2.3.2 Sensor Discussion

It is well known that there are a number of military applications of infrared techniques for detecting targets by their self emission of wavelengths in the bands of 3-5 and 10-12 microns corresponding to the existence of atmospheric windows where such wavelengths are relatively unattenuated.

In general, these may be subdivided into search and track applications, and thermal imaging applications. Passive search and track systems, such as the IRST (AN/SAR-8) system, have become useful as a stealth complement to radar, but are not designed to "measure" the target's signature. Thermal imaging techniques, on the other hand, uses hot areas emitting from the target to not only detect, but to recognize and identify targets. Such capability implies the need for the necessary sensitivity and resolution in a sensor to gauge changes in the target's IR signature in real time, and to attempt to relate such effects to a specific cause of interest (in this case, trajectory alteration).

3.2.3.3 Target Definition

While the specific threat characteristics are classified, some "generic values" can be assumed in order to depict the relevant parameters of the threat which affect its infrared signature.

Threat:	Anti-ship missile	
Speed:	300 - 900 m/sec	
Altitude:	25 metres (sea skimmer)	
	10,000 metres (diver)	
Softkill Engagement Range:	10 km (trajectory 1)	
	30 km (trajectory 2)	
Normal Viewing Aspect:	0° (head on)	
Softkill Induced Trajectory Deviations:		
Amplitude:	$\pm 1.5^\circ$	(trajectory 1)
	$\pm 8^\circ$	(trajectory 2)

3.2.3.4 Factors Affecting Radiant Intensity

The radiant intensity of an anti-ship missile at a given wavelength or within a given band of wavelengths (such as 3 - 5 μ) will be a function of a number of independent variables. These may include:

Viewing Aspect;
Rocket Motor Status (boost, post boost, etc.);
Range;
Speed (due to skin heating effects);
Atmospheric conditions;
Altitude (probability of clear line-of-sight from sensor); and
Atmospheric Turbulence.

Each of these will be addressed in turn.

(1) Viewing Aspect

From data on radiant intensity of missiles and aircraft as a function of viewing aspect, we may conclude several things:

- i. Variation in radiant intensity as a function of azimuthal changes on the order of 1.5 degree variations in aspect angles are:
 - a. small in absolute terms (Figure 3-20, Figure 3-21) ;
 - b. small in relation to variations due to other time variant effects (such as range closure and atmospheric scintillation); and
 - c. not monotonic (Figure 3-22).

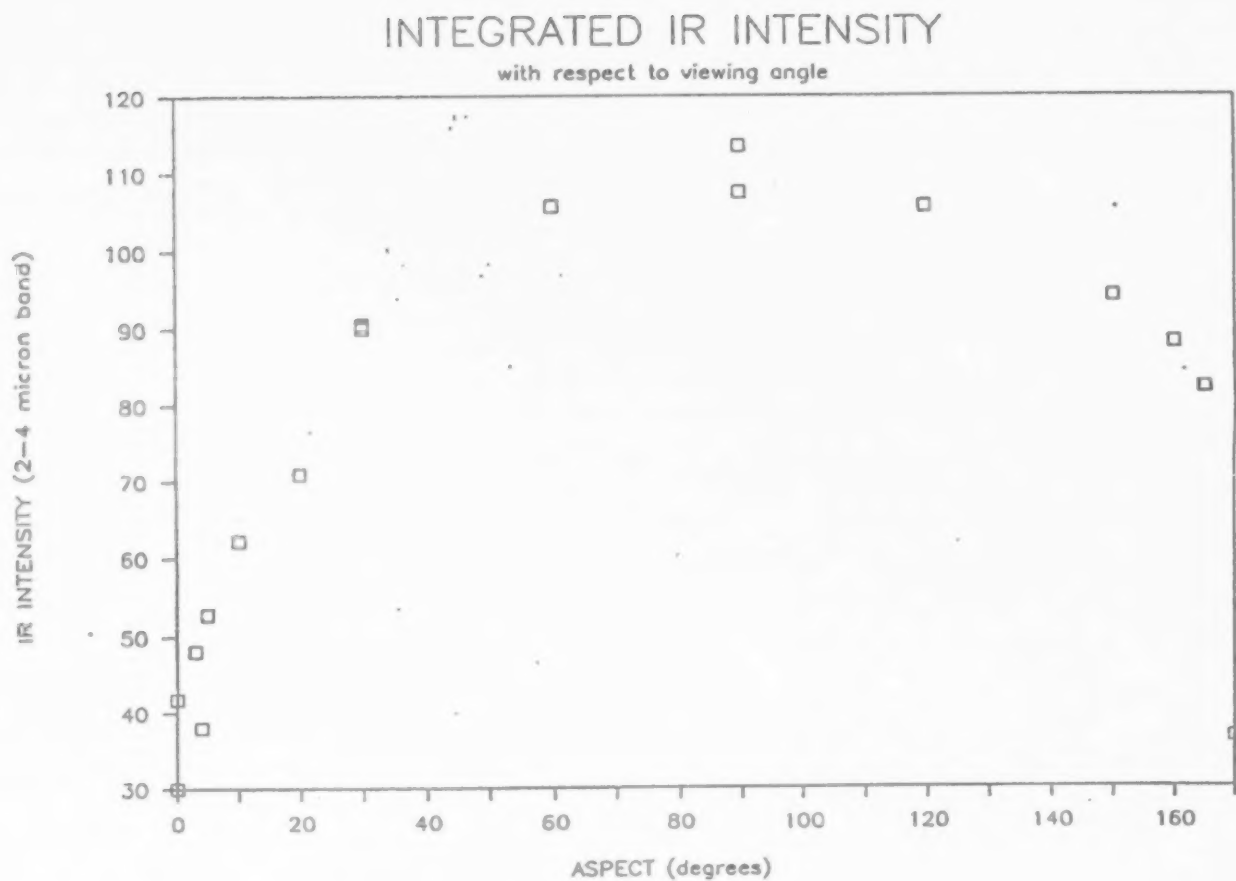


Figure: 3-20 Integrated IR Intensity vs Aspect Angle (Tethered Rocket Motor)

Jet Signatures vs Viewing Aspect

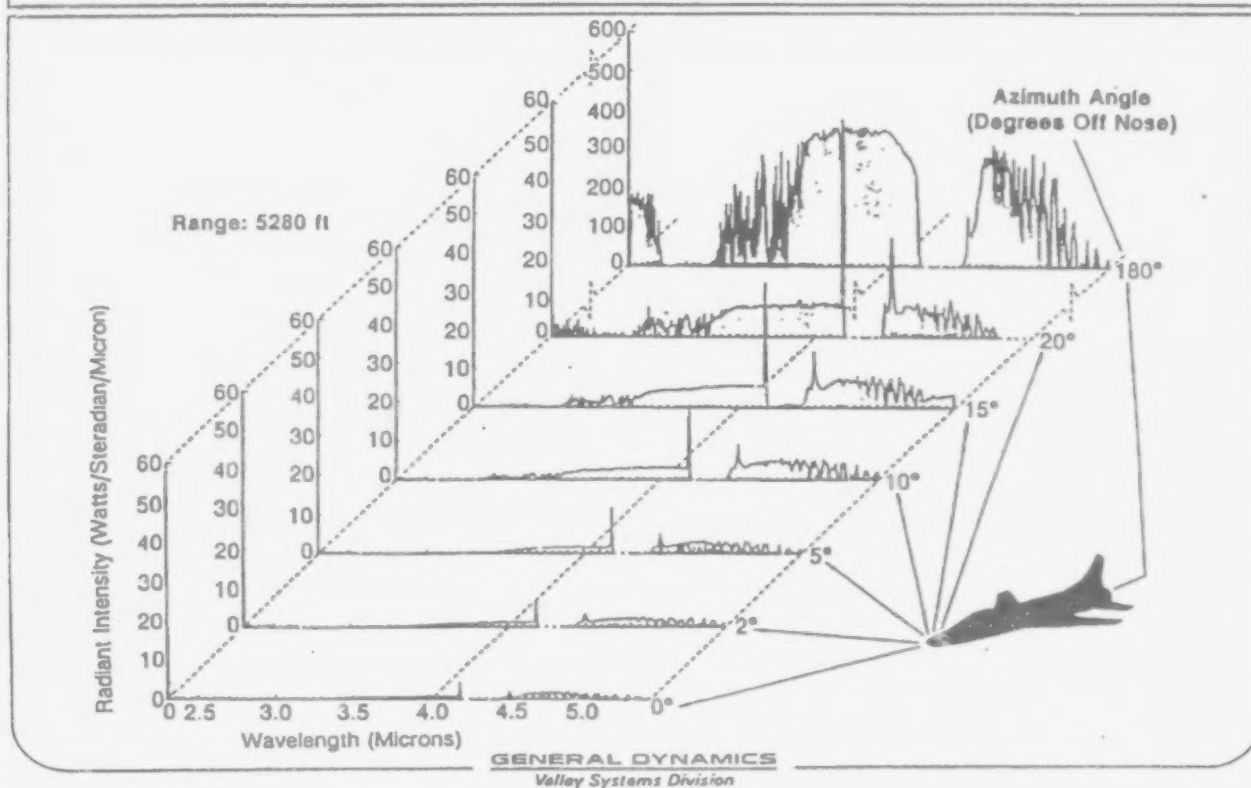


Figure: 3-21 Jet IR Signature vs Aspect Angle

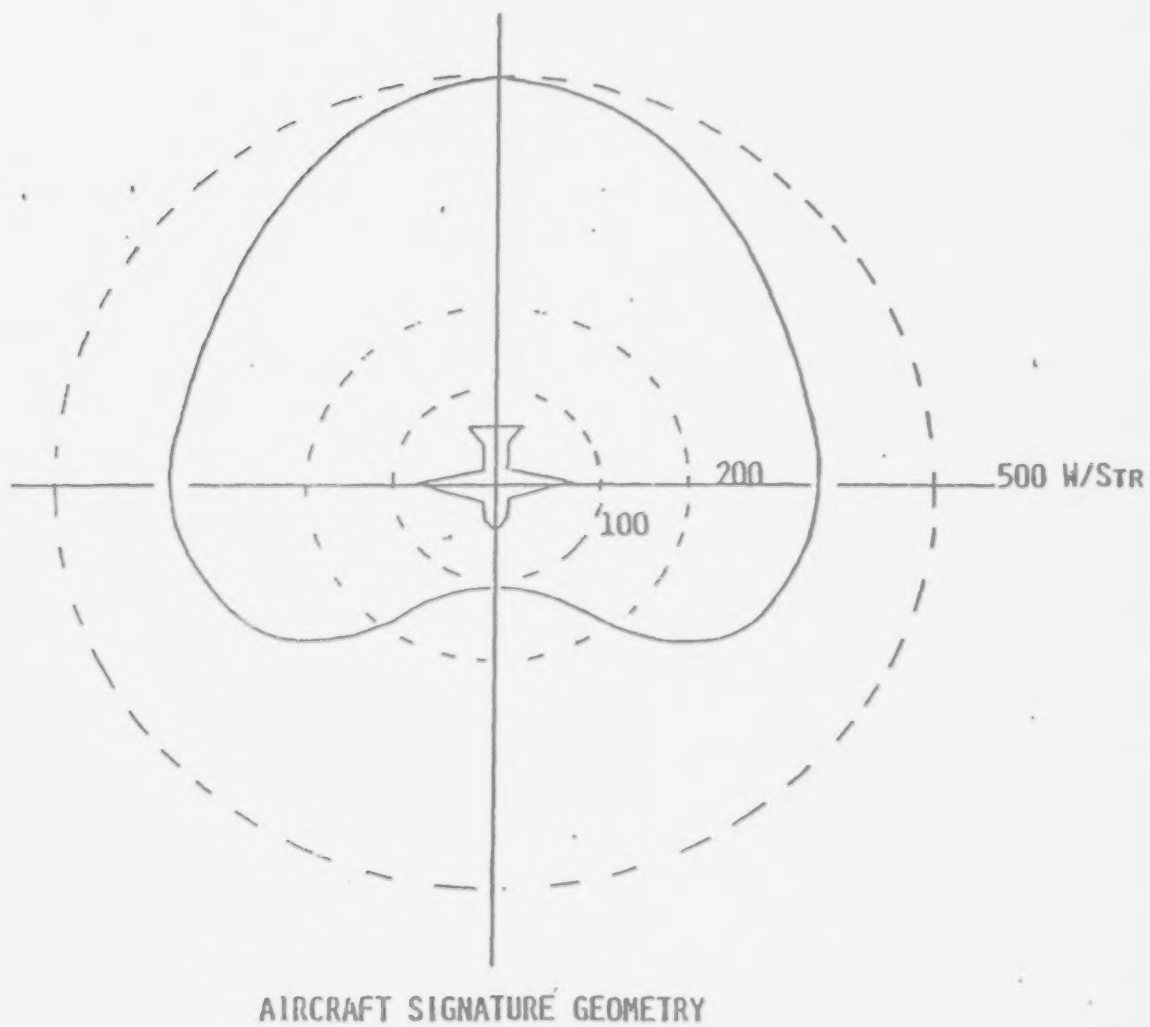


Figure: 3-22 Aircraft IR Signature vs Aspect Angle

Note regarding Figure 3-20: The information represented in this plot provides the results of DREV tests of a tethered rocket motor. These tests were not conducted to support the NEWCP and have been provided by DREV in response to a request by LCAN / Thomson Systems. LCAN / Thomson Systems assumes responsibility for the use of these results within the context of this report.

- ii. A more difficult complication stems from the fact that we are looking at a band of infrared frequencies. The various parts of the target are at different temperatures and therefore, from Wein's Law, we know that these parts exhibit peak spectral photon existence at different wavelengths according to their temperature. For example, the plume radiation may be at one temperature, the hot metal surrounding the rocket motor(s) at a second temperature, and the forward part of the missile, subject to skin heating effects due to its supersonic speeds, at yet a third temperature. The net result is that the infrared signature, integrated over a band of IR wavelengths, varies with azimuth in a complex fashion, since it is not only the viewing aspect which is involved, but the composition of the target which is being viewed at a given aspect. Other factors, such as the emissivity of the target, the nature of the background, environmental factors such as sun glint, etc., also make the signature and the contrast irradiance more difficult to anticipate (Figure 3-23).

(2) Range

Since the radiant intensity varies as $1/R^2$, and since the threat is travelling at, say, Mach 2.5 (900 metres/second), the apparent radiant intensity will increase rapidly and non-linearly with time. We have assumed that the threat will be engaged at distances of 10000 metres in one case. If the radiant intensity of the target was x Watts/steradian at 10 km range, it would be $1.21x$ (i.e., 21% higher) only 1 second later due to the reduction in range. Changes of this magnitude over periods as short as 1 second could far outweigh any changes due to trajectory alterations.

(3) Speed

Tests and calculations done for aircraft such as the Concorde, the Boeing 733, the X-15, and the XB-70A have shown that at speeds between Mach 2 and 3 the equilibrium surface temperature caused by aerodynamic heating for altitudes above 10,000 metres, ranges between 100 and 300° C. At lower altitudes, one assumes this would be considerably higher, and for a high diver transitioning from high to low altitudes, the effects may be quite complex.

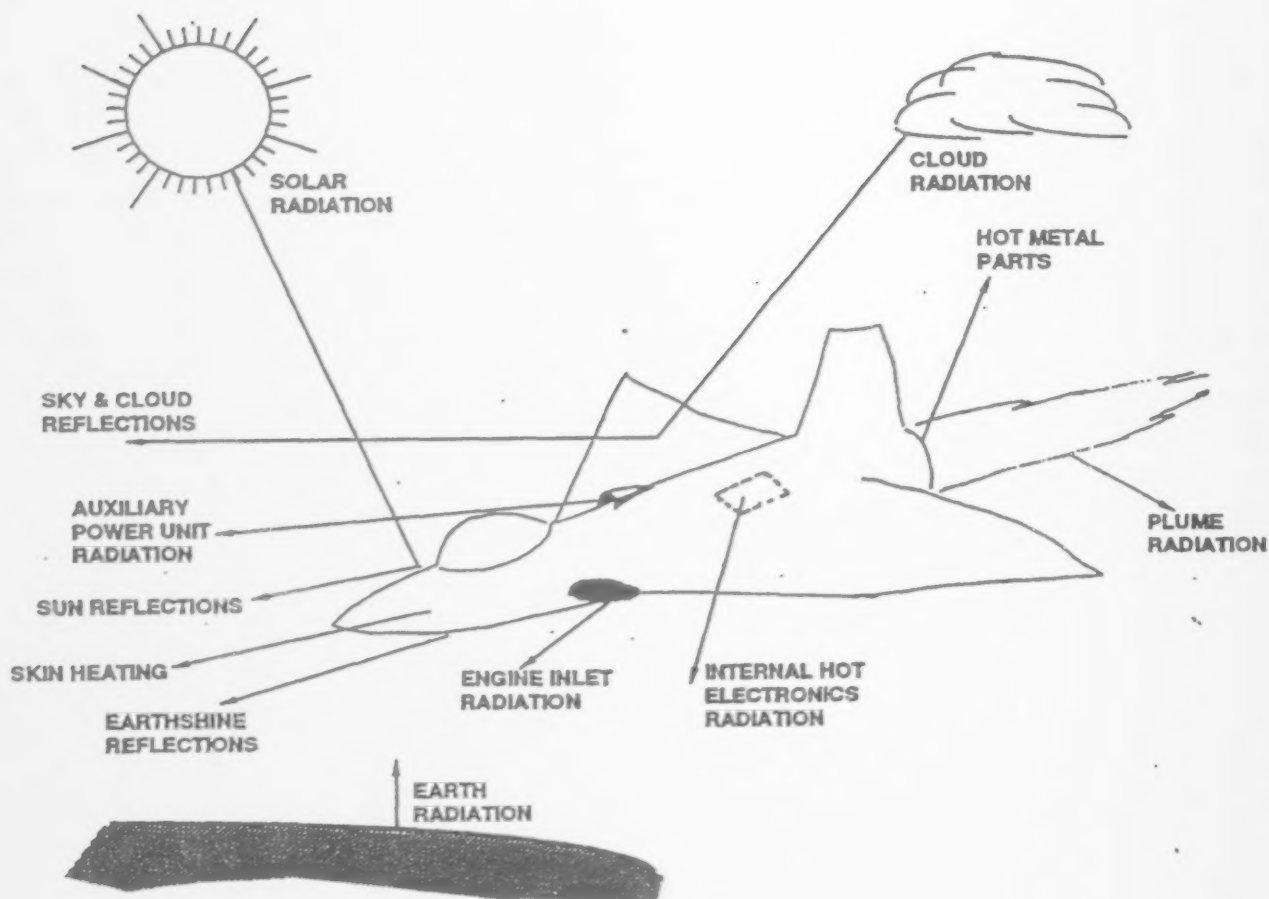


Figure: 3-23 Sources of IR Energy (Including Environmental Sources)

(4) Altitude

In addition to the altitude effects discussed above, there exists, for a given target/sensor altitude difference, a probability that there will not be a clear line of sight path due to cloud cover. For example, for a sensor at sea level and a target at 5000 metres, with a horizontal separation of 10,000 metres, there is about a 70% chance of having a cloud free layer through which IR line-of-sight is possible.

(5) Atmospheric Conditions

Most atmospheric scintillation effects have been measured at visible, rather than IR, wavelengths. Nevertheless, infrared systems are similarly affected. Two major effects of scintillation are observed, either singly or in combination: variation in radiant intensity from the distant source (amplitude modulation), and variation in the apparent direction of the source. Amplitude variations of 65% over 1 kilometre distances have been noted, at frequencies to 9 Hz. In terms of variation in direction, several arc seconds of variation have been measured.

Other factors, such as fog, rain, snow, cloud cover, etc. seriously impair the ability of an IR sensor to detect a target.

3.2.3.5 Conclusions

Based on the foregoing discussion, we believe that changes in the trajectory of an anti-ship missile could not be detected using thermal imaging techniques, since changes in the signature of such a target due to such differences in the resultant viewing aspect would be masked by numerous other more significant effects which would render the task unreliable at best, and probably impossible.

3.2.4 Apparent Missile Length Changes

3.2.4.1 Introduction

The purpose of this section of the report is to address the feasibility of using radar in order to measure the apparent change in length of an anti-ship missile (ASM) as it changes direction due to the effects of countermeasures deployment. The idea is to take advantage of the fact that the apparent length of the missile, measured along the line of sight from the ship to the missile, will change as the heading of the missile changes. A radar has the capability, at least in principle, of measuring the extent of the target specifically along the axis defined by the radar line of sight. For a threat having a purely radial in-bound trajectory, the extent of the threat along the radar line of sight is equal to true missile length. As the missile changes its heading away from the ship, the length of the threat, measured along the radar line of sight will decrease. In the extreme case where the threat is flying a course 90° displaced in angle from a true radial in-bound trajectory, the apparent length of the missile will equal the true width of the missile.

This section of the report addresses the following: i) description of relevant tactical scenarios, ii) discussion of the feasibility of the proposed approach; and iii) conclusion.

3.2.4.2 Relevant Tactical Scenarios

The purpose of this sub-section is to estimate the magnitude of changes in apparent missile length within the context of realistic engagement scenarios. Once the magnitude of expected missile length changes has been estimated, the feasibility of the proposed method (as described in the introduction) can be properly addressed.

For the purposes of this discussion, we consider two representative engagement scenarios. The first of these involves the use of a decoy deployed for the purposes of confusion; to provide an alternate target for the threat seeker during the search / acquisition phases of its operation. We assume that the threat is initially flying a purely radial-inbound trajectory. At a range of 30 km it acquires a decoy which is deployed at a range of 1500 m from the ship. The simplifying assumption is made that the threat immediately changes its heading and flies straight toward the decoy. Note that a missile threat at a range of 30 km will be visible to ship sensors as long as its altitude exceeds ≈ 15 m (for an assumed radar height above the waterline = 10 m).

We are interested in determining the apparent reduction in missile length of the threat at the instant that it undergoes the change in heading described in the above paragraph. Referring to figure 3-24, it can readily be seen that the change in apparent missile length is given by the $(L_1 - L_2)$. We assume that the true length of the missile (equal to L_1) is approximately 3 - 5 m. Simple geometrical calculation result

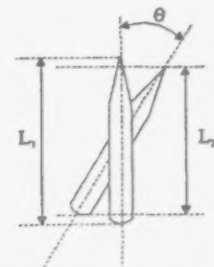


Figure 3-24 Missile length change

in an apparent missile length change < 1 cms.

The second scenario involves the use of a decoy deployed for the purposes of seduction; to cause the threat seeker lock to be transferred to the decoy without inducing a change in threat radar state. Again it is assumed that the threat is initially flying a purely radial in-bound trajectory towards the ship. At a range of 15 km from the ship it is assumed that seeker lock is transferred to a seduction decoy that is deployed at a range of 150 m from the ship. The simplifying assumption is made that the threat immediately changes direction and begins heading for the decoy.

Simple geometrical calculations, similar to those performed for the confusion engagement scenario described above, yield an expected reduction in apparent missile length $\ll 1$ cm.

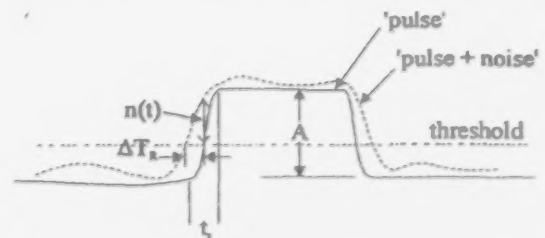
3.2.4.3 Discussion of Technique Feasibility

It seems intuitively obvious that the proposed method for effectiveness assessment will not be feasible due to the extremely small changes in apparent missile length. Missile length changes of less than 1 cm will likely be smaller than the wavelength of a radar that might be used to measure such changes.

Even though the technique appears to be not practical, it is worthwhile addressing some of the technical issues involved in the measurement of the physical extent of an arbitrary body along the radar line of sight.

The measurement of the range to a radar scatterer is accomplished by measuring the round trip time associated with a radar pulse that travels to the scatterer and then is reflected back to the radar receiver (assuming co-located radar transmitter and radar receiver). Symbolically, $T_R = 2R/c$, where R is the range to the scatterer and c is the speed of light. However, the presence of noise limits the accuracy with which range can be measured by radar, which is discussed in more detail below.

One method for determining target range involves the measurement of the time at which the leading edge of a pulse crosses some threshold (refer to the figure below). The pulse, uncorrupted by noise, is depicted by the solid line; as indicated, the pulse is not perfectly rectangular in that it has rise times and decay times that are not $= 0$. To achieve a rise time $=$ decay time ≈ 0 would require an infinite bandwidth. The dashed line is a representation of a pulse that is corrupted by noise; the significant effect is the shift in the time of threshold crossing as compared to the noise-free pulse.



The maximum slope of the leading edge of a pulse of amplitude A at the output of a video filter is A/t_r , where t_r is the pulse rise time. It can be seen that for large signal to noise ratios, the slope of the pulse corrupted by noise is approximately equal to the slope of the uncorrupted pulse. As seen in the figure, the slope of the pulse in noise $= n(t)/\delta T_R$, where $n(t)$ is the noise voltage in the vicinity of the threshold crossing and δT_R is the error in the time delay measurement. Equating the two expressions for slope yields [skolnik]:

$$\Delta T_R = \frac{n(t)}{A/t_r}$$

or

$$[(\Delta T_R)^2]^{1/2} = \delta T_R = \frac{t_r}{(A^2/n^2)^{1/2}} = \frac{t_r}{(2S/N)^{1/2}}$$

where

A^2/n^2 is the video signal to noise (power) ratio.

The last part of the equation follows from the fact that the video signal-to-noise power ratio is equal to twice the IF signal-to-noise power ratio (S/N), assuming a linear detector law and a large signal-to-noise ratio. Now, the equation can be rewritten in order to get an expression for signal-to-noise ratio, $S/N = t_r^2 / (2\delta T_R^2)$. A range difference of 1 cm equates to a time differential of $\Delta T_R = 2\Delta R/c \approx 6.7E-11$ s. To measure this properly would require a time accuracy less than this, on the order of say 0.02 ns. Furthermore, we assume that the smallest rise times achievable in practice are on the order of $1E-9$ s (1 nanosecond). With these two data, the signal-to-noise ratio (S/N) required in order to obtain the desired range would be ≈ 111 dB. Such a high S/N value is not achievable in any kind of realistic scenario involving a shipborne radar and an anti-ship missile. It can be therefore concluded that the required measurement accuracy (< 1 cm) cannot be achieved with a normal pulsed radar and the proposed method for effectiveness assessment is not a realistic option.

The table below provides some insight into the types of accuracies that can be theoretically obtained for different radar IF bandwidths and signal-to-noise ratios for a pulsed radar. Bandwidths of 10, 20 and 30 MHz are calculated for typical S/N ratios of 0 to 60 dB. The numbers inside the table represent the time measurement accuracy, δT_R , expressed in nanoseconds. The table shows that in order to obtain an accuracy of 0.02 ns with a S/N ratio of 60 dB, a bandwidth of 30 MHz would be required. Such a wide bandwidth would result in more noise entering into the receiver, ultimately decreasing the S/N ratio. To compensate, more power would have to be transmitted. However, the amount of power that is required, given the size of typical anti-ship missiles and the ranges at which these measurements have to be made, cannot

Bandwidth (MHz)	S/N						
	0	10	20	30	40	50	60
10	70	22	7.1	2.2	.71	.22	.071
20	35	11	3.5	1.1	.35	.11	.035
30	24	7.5	2.4	.75	.24	.075	.024

be practically obtained.

Pulse compression radars offer improved range-resolution while utilizing a long pulse to achieve large power returns. Since the radar is capable of good range-resolution, it is also capable of good range accuracy [skolnik]. However, the magnitude of the accuracy, based on the current technology, is still not sufficient for measuring apparent missile length changes. Pulse compression ratios (PCR) of 100 up to 10000 (with SAW devices) are possible, yielding effective pulses as narrow as 5 ns, which is still not sufficient for our application. As the technology improves in the devices used to achieve higher compression ratios, a number of issues need to be addressed, including: i) the transmit peak power has to be reduced for longer pulses to meet transmitter amplifier duty cycle constraints (resulting in a lower SNR), ii) higher PCRs introduce range sidelobes which reduce the dynamic range of the receiver (weighting factors may be used to minimize this problem to some extent), and iii) the longer pulse restricts detection of close-in range missiles. The APAR system, soon to be fitted aboard the CPF, is a pulse compression radar with a range resolution capability on the order of a few meters.

There are a variety of other effects and phenomena which limit the practicality of the proposed approach. It is almost certain that instabilities in the navigation control loops will cause the threat heading to vary appreciably compared to heading variations attributable to effective countermeasure action. This might be the case even if the seeker is tracking the ship and has not been deceived. There may also be some range glint which could introduce errors in range measurement comparable to what is being measured.

3.2.4.5 Conclusion

The method of using apparent changes in missile length in order to infer that a trajectory change has taken place appears to be impractical for a variety of reasons. To measure such minute changes requires extremely high range tracking accuracy, which implies very short rise times (extremely large bandwidths) and a large signal-to-noise ratio. Given the performance of existing radars and the RCS of typical anti-ship missiles, this technique appears impractical at this time.

3.3 JOG DETECTION

This section provides a description of the term 'jog' as it applies to EW and the possible methods by which it can be measured. A jog refers to a sudden movement of the tracking radar's antenna away from target boresight due to jamming. The antenna can deflect, or jog, at very slight angles or large ones exceeding the antenna's HPBW. The rate of deflection can also vary from just above 0 deg/s up to the maximum limit imposed by the radar's antenna servos. The scanning behaviour of the jog also varies widely, depending on the type of jamming applied. For example, the antenna can swing in a linear direction away from boresight, or in a quazi-circular or random pattern about boresight. The ability to measure a jog event is significant to the NEWCP processor, as it indicates the precise moment jamming has perturbed the tracking process of the threat radar. With this instant feedback, the NEWCP and its subordinate ECM assets can continue to deploy/refine those ECM techniques most effective against the enemy's tracking radar, thus enhancing ship survivability.

There are several possible approaches to detecting and measuring a jog event, each with there own set of advantages and disadvantages (i.e. trades). This section investigates four specific jog assessment techniques, which are based upon antenna reflections, amplitude changes, X-pol/Co-pol variations, and off-boresight multipath diffraction effects. For each technique, the various factors affecting their performance are addressed, including: sensor limitations, environmental effects such as multipath, clutter, etc.

Antenna Reflections:

This technique involves transmitting a radar signal from own ship, and then measuring the energy reflected from the seeker's antenna. The moment the seeker antenna undergoes a jog, the jog detector (JD) radar measures a corresponding decrease in received energy, as the signal is reflected in a different direction.

X-pol/Co-pol Variations:

This technique involves measuring the change in the X-pol/Co-pol energy ratio as the seeker antenna experiences a jog.

Amplitude Changes:

This technique involves measuring a decay in received power from the seeker as the antenna jogs away from boresight. Several means of achieving this measurement exists, including using temporal and spatial diversity, particulary to offset the adverse effects of multipath.

Off-boresight Diffractive Effects

The diffractive effects of multipath reflections from rough seas is more pronounced off boresight

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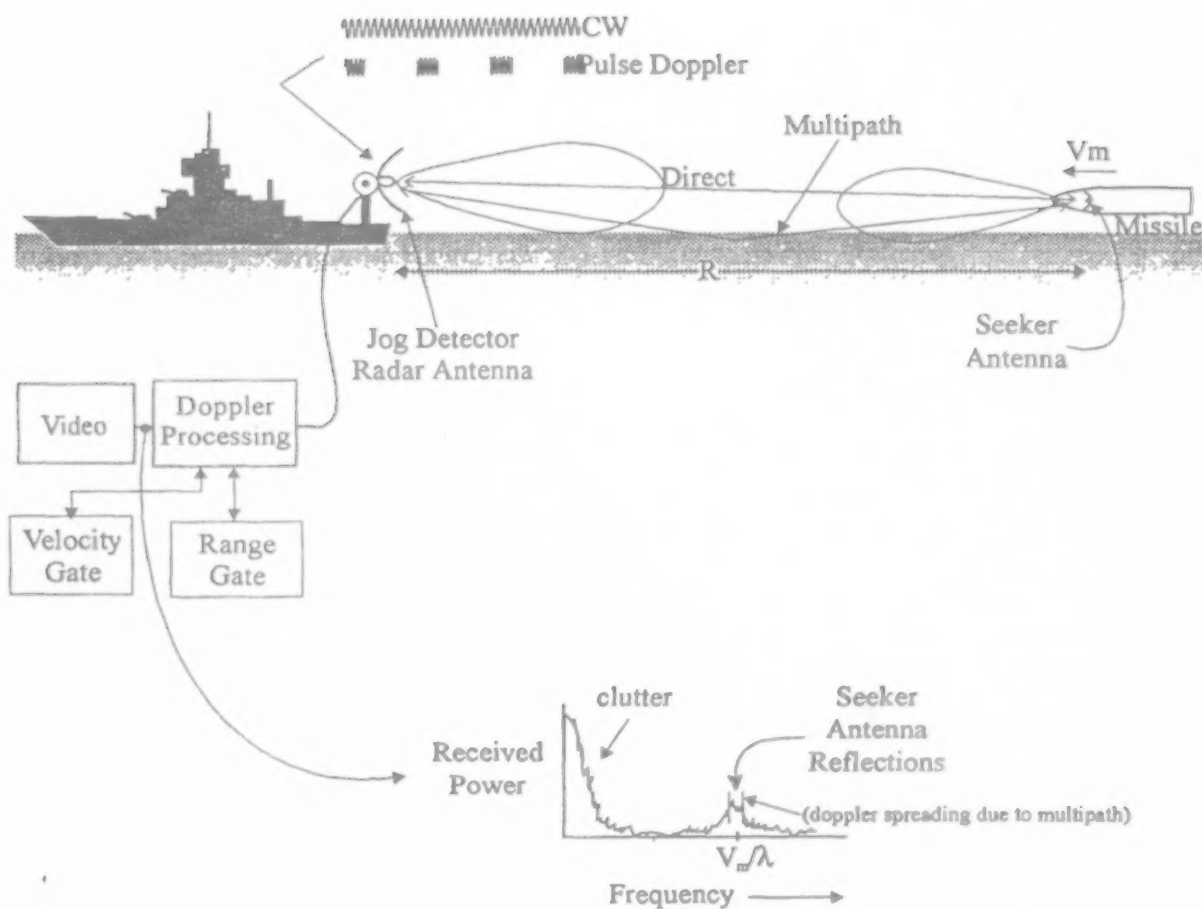


Figure 3-25 Setup for radar jog detection using seeker antenna reflections

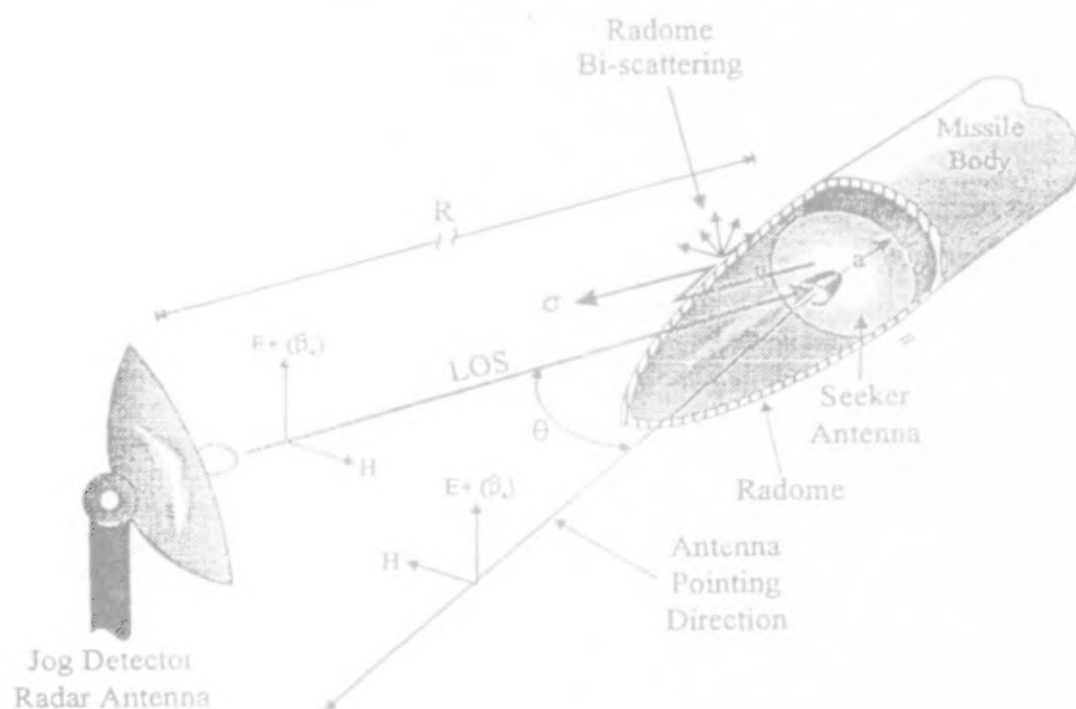


Figure 3-26 Definition of terms for seeker antenna reflections JD method

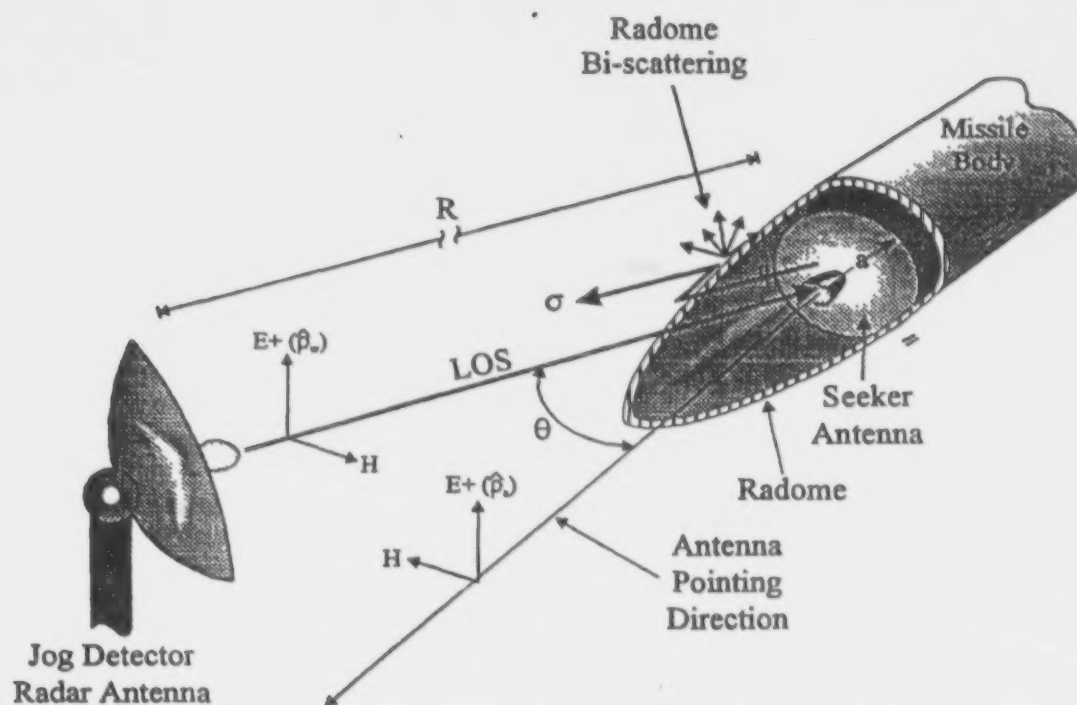


Figure 3-26 Definition of terms for seeker antenna reflections JD method

extent defined by the antenna's VSWR). This assumes the JD radar is transmitting in-band with that of the seeker antenna. On the other hand, if the incident polarization is orthogonal to that of the seeker antenna, then a high mismatch results, producing maximum scattering. As just alluded to, frequency also determines the extent to which antenna reflections occur. The in-band response produces less reflections than out-of-band. For the in-band case, the seeker antenna is designed to optimally receive its own backscattered signal with minimal reflections. Therefore, an interrogating signal, such as one originating from the JD radar, which operates at the same frequency, observes a much lower RCS. On the other hand, if the JD radar operates outside the frequency bandwidth of the seeker antenna, then the antenna looks predominantly reflective, and the amount of energy reflected is based on, among other things, the effective aperture size (or gain) of the antenna. A higher frequency is advantageous, as it yields reflected signals with higher directivity, making jogs easier to measure (this is discussed in more detail below). Typical bandwidths for anti-ship missiles are approximately 5-10% of the operating frequency. This number drops significantly for flat plate arrays, which exhibit very high Q's.

There exist two fundamental components of antenna reflections, referred to as radiation and structural mode responses [1&2]. The radiation mode response is defined as energy that is transmitted by the antenna through normal excitation by an external source, such as the JD radar, rather than the antenna's own transmitter. The actual phenomenon is a re-radiation of the incident electromagnetic wave, which produces currents onto the antenna elements (for array) or aperture, creating electric fields for radiation. Structural mode response refers to energy that is reflected off the antenna, external antenna structures and support, radomes, and installation cavities.

A paper, written by R. C. Hansen [4], describes in general terms the contributing components of antenna RCS, striking a relationship between the reflected and radiated electrical fields. Unfortunately, the paper does not explicitly define the scattering phenomena associated with each mode, nor their dependence on antenna type. For example, the following equation is presented, showing the two mode responses of the antenna,

$$\sigma = \left| \sqrt{\sigma_{\text{structural}}} - (1 - \Gamma_a) \sqrt{\sigma_{\text{antenna}}} \exp \phi_{\text{rel}} \right|^2 \quad (34)$$

The first term refers to the structural mode, while the second is the radiation mode response. The expression ϕ_{rel} is the relative phase between both terms. Equation 34 describes the scattered field as equivalent to the short circuit field (structural mode) plus a factor of $(1 - \Gamma)$ times the radiated field. In other words, the antenna RCS is equal to the total energy reflected from the antenna, when it is shorted, minus the energy absorbed by the antenna under a normal match. The terms $\sigma_{\text{structural}}$ and σ_{antenna} and ϕ_{rel} are not defined, while other factors, which are known to affect RCS, are not addressed, including polarization mismatch, antenna beamwidth and aspect sensitivity, etc.

There is, obviously, a strong mutual interaction/coupling between the fields created by the radiation and structural mode responses which is not explicitly defined in equation 34. It is well outside the scope of this study to characterize this phenomena from basic electromagnetic

principles. This paper attempts to bring forth some of the issues relevant to antenna RCS and provide insight into the types of energy levels that may be expected from simple antenna configurations for each mode. Further theoretical analysis and/or experimentation is required to obtain a more thorough understanding and characterization of the phenomenon.

3.3.1.1 Radiation Mode Response

An approximation of the monostatic radiation mode RCS of an antenna is given as [1,3]:

$$RCS = \sigma = \Gamma^2 \frac{G^2 \lambda^2}{4\pi} \quad (35)$$

where G = gain of the seeker antenna,

λ = wavelength, and,

Γ = antenna reflection coefficient based on impedance and polarization mismatches, and conduction and dielectric losses.

Equation 35 is simplistic, with many assumptions/parameters integrated into the coefficient Γ , so that very little insight is given into the actual mechanism involved in the reflection process. It appears, from the literature search performed under this study, that this topic has received little attention in the scientific community. The overall process involved in antenna reflections, with radomes, is quite complex.

Polarization mismatch is determined by the polarization loss factor (PLF), expressed as [3],

$$PLF = |\hat{\rho}_w \cdot \hat{\rho}_a^*|^2 = |\cos \Psi_p|^2 \quad (36)$$

where

$\hat{\rho}_w$ = incident polarization unit vector,

$\hat{\rho}_a^*$ = receiver polarization unit vector conjugate, and,

Ψ_p = polarization alignment angle between the JD radar and the seeker antenna.

The angle Ψ_p is shown in figure 3-27 for aligned, orthogonal and rotated relationships between the transmit and receive antennas. When the two antennas are perfectly aligned (co-polarized), the PLF factor is equal to 1, while an orthogonal link implies a PLF of 0. From equation (36), a PLF of 0 yields a maximum RCS, while a PLF of 1 results in minimal reflections.

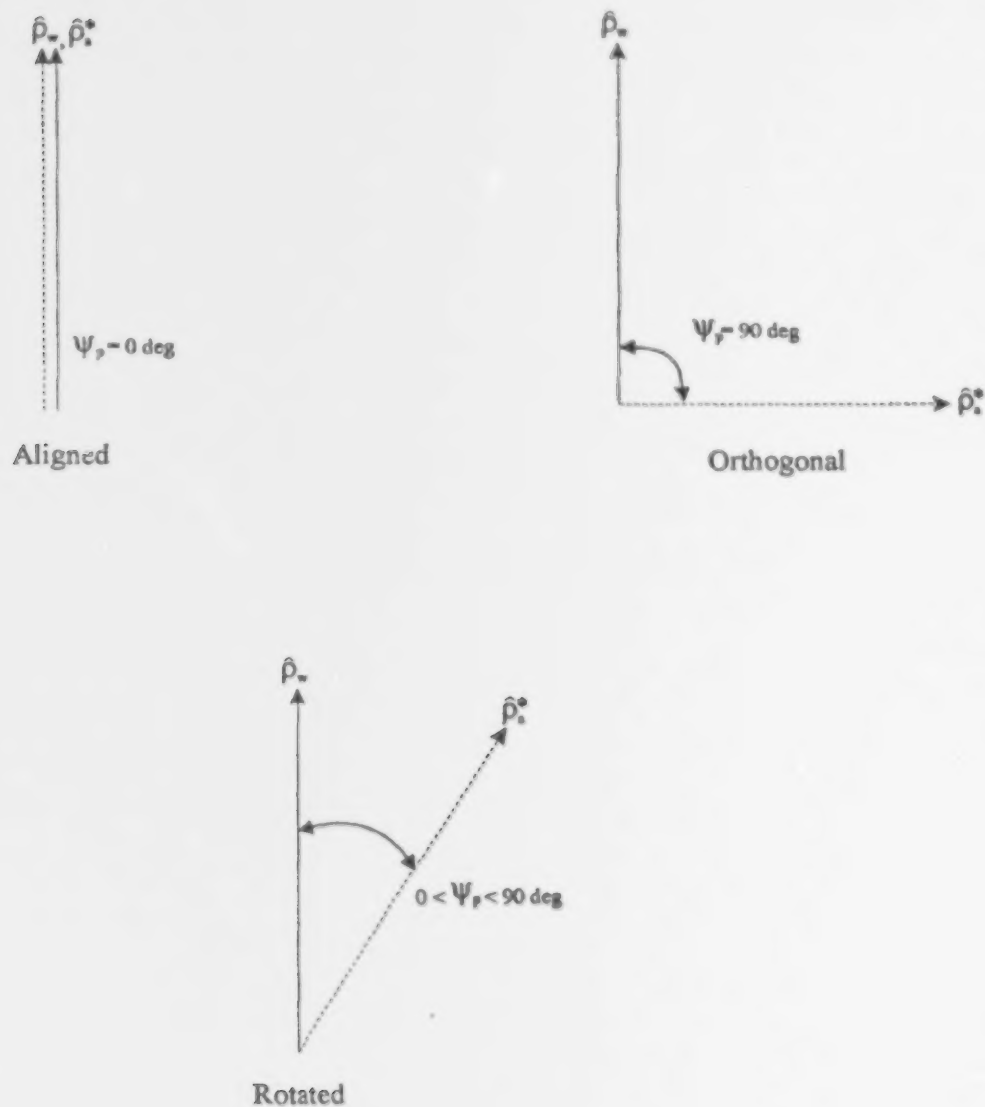


Figure 3-27 Polarization relationships between JD radar and seeker antennas

The VSWR of the antenna determines the reflection coefficient, ρ , of the antenna as follows,

$$|\Gamma| = \frac{1 - \text{VSWR}}{1 + \text{VSWR}} \quad (37)$$

The VSWR for a typical paraboloid antenna is roughly 2:1, therefore, the corresponding reflection coefficient is 0.333. The conduction (e_c) and dielectric (e_d) efficiencies of the antenna are factored in through the gain of the antenna.

Taking into account the polarization loss factor, impedance mismatch of the antenna, and the radiation pattern of the circular aperture, equation (35) may be written as [balanis]

$$\sigma = \text{RCS} = |\hat{\rho}_w \cdot \hat{\rho}_a|^2 \rho^2 \frac{G^2 \lambda^2}{4\pi} \left[2 \cos(\theta) \frac{J_1 \left(\left(\frac{2\pi}{\lambda} \right) a \sin \theta \right)}{\left(\frac{2\pi}{\lambda} \right) a \sin \theta} \right]^2 \quad (38)$$

where,

J_1 = Bessel Function of the first kind, order one,

a = radius of the seeker antenna aperture,

θ = angle between incident signal and seeker antenna boresight.

The Bessel function describes the radiation pattern for a circular aperture antenna, over the azimuth angle θ . θ is the angle between the incident signal (LOS) and seeker antenna pointing direction. It is assumed, for typical sea skimming anti-ship missiles, that the seeker antenna is boresighted to the horizon in the elevation plane. Hence, the radiation pattern in the vertical sense is set to unity for all angles of θ . From equation 38, it is observed that high gain antennas with poor impedance matches exhibit the highest RCS responses.

The physical aperture, A_p , of the circular seeker antenna is πa^2 . Assuming an antenna radius of 0.2 m, then A_p is equal to 0.126 m². The effective aperture (A_e) of a circular antenna is generally less than its physical aperture size due to losses and diffractive effects, and tapered illumination to reduce sidelobes. The antenna's aperture efficiency, ϵ_{ap} , is defined as,

$$A_e = \epsilon_{ap} A_p$$

For circular apertures, ϵ_{ap} can fall between 50 % < ϵ_{ap} < 80 % [3]. For the purpose of this study, ϵ_{ap} is assumed to be 60 %.

The gain of the seeker antenna is,

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi(0.076)}{(0.033)^2} = 877 = 29dB \quad (39)$$

Given the above parameters, the RCS of the seeker antenna at boresight, for co-polarized alignment, is,

$$\sigma = \frac{(1)^2 (0.333)^2 (877)^2 (0.0333)^2}{4\pi} \left[\frac{J_1[(2\pi/0.033 \cdot 0.2 \sin(0))]}{(2\pi/0.033 \cdot 0.2 \sin(0))} \right]^2 \quad (40)$$

$$\sigma = 7.3 \text{ m}^2.$$

Therefore, the in-band radiation co-pol response RCS of the seeker antenna itself is 7.30 m².

The radiation mode RCS of the seeker antenna can now be applied to the 2-way radar range equation to determine the amount of energy received by the JD radar, at say a range of 15 km. Assume a radar with a transmit power of 10 kw, a gain of 35 dB, and a frequency wavelength of 0.033 m, then, the received power is equated as,

$$P_{rec}(dB) = 10 \log \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \right) = 10 \log \left(\frac{10000 \cdot 3162^2 \cdot 0.033^2 \cdot 7.3}{(4\pi)^3 \cdot 15000^4} \right) = -111 \text{ dBm} \quad (41)$$

where,

P_t = JD radar transmit power (w),

G = JD radar antenna gain, and

R = radial range between JD radar and missile.

A received power level of -111 dBm is expected for a seeker antenna situated 15 km away from the jog detector radar, for in-band and co-pol conditions.

As mentioned earlier, the polarization loss factor determines the extent to which the antenna looks reflective. If the PLF is equal to 1, i.e. co-polarization alignment, then minimal scattering takes place while a PLF of 0 implies total reflection. As the polarizations of both antennas deviate from co-pol alignment, bi-scattering or structural mode reflection becomes the predominant factor. As will be described, structural mode reflections yield much higher power than the radiation mode.

3.3.1.2 Structural Mode Response

The structural mode response of an antenna is complicated to mathematically describe, since there are many physical shapes and sizes contributing to the reflection phenomenon, including the antenna itself, antenna supports, feed horn, radome, X-pol grids (if they are implemented), etc. The different classes of antennas also vary widely, ranging from flat plate arrays to polarization twisting cassegrain - each affecting the behaviour of biscattering differently. As noted earlier, it is outside the scope of this paper to analyse the biscattering properties of different antennas, however, it is possible to gain insight into the types of RCS levels that can be expected for the simplest case, i.e. flat plate circular aperture antenna.

Ignoring coupling effects from the radiation mode, the far field structural mode response (RCS) of a circular flat plate antenna, without supporting structure or radome, is [skolnik, balanis]

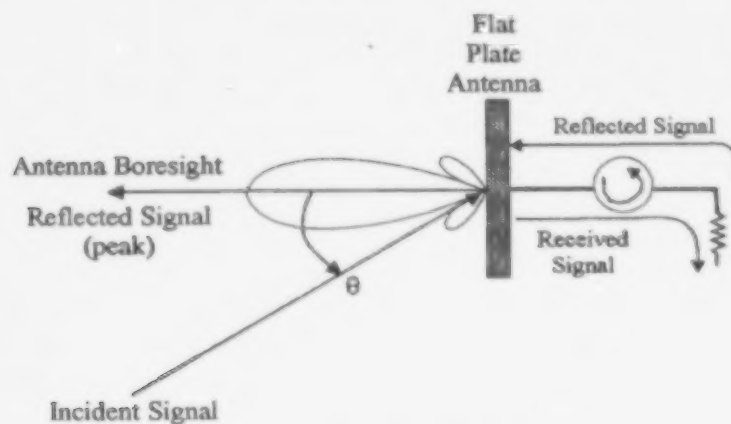
Factoring in the polarization loss factor yields,

$$\sigma = RCS = \frac{G^2 \lambda^2}{4\pi} \left[2 \cos 2\theta \frac{J_1(ka \sin 2\theta)}{ka \sin 2\theta} \right]^2 \quad (42)$$

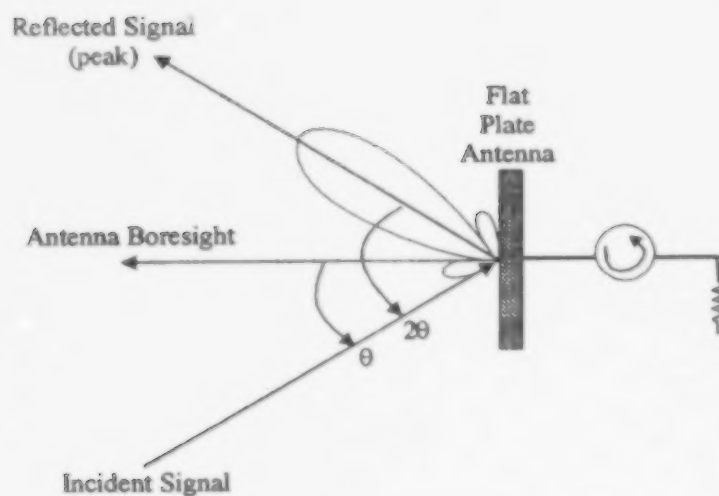
$$\sigma = RCS = (1 - |\hat{\rho}_w \cdot \hat{\rho}_a|^2) \frac{G^2 \lambda^2}{4\pi} \left[2 \cos 2\theta \frac{J_1(ka \sin 2\theta)}{ka \sin 2\theta} \right]^2 \quad (43)$$

The above equation describes a biscattering phenomenon, which is different from the radiation mode of equation 38. One principal difference between both equations is the "sin 2θ" term, which indicates that the power response at the jog detector for the biscattering case is related to twice the angular movement of the seeker antenna. Refer to figure 3-28 for an illustration of the difference between radiation mode and structural mode response.

As shown in figure a, for the radiation mode scattering, the energy is absorbed by the antenna and then reflected back out to the antenna due to impedance mismatch. The actual process is described as follows. Once the incident signal is absorbed by the antenna, all phase information describing the pointing vector (angle of arrival) of the signal is lost, due to the individual fields combining in the waveguide to yield a single vector. Since there is impedance mismatch in the load, some of the incident signal is reflected back out to the antenna, and re-transmitted. The resultant output signal propagates into freespace, with its mainbeam pointing in the direction of the antenna's physical boresight position. Consequently, for every degree of θ the antenna jogs, the JD radar observes a power response equivalent to θ.



a) Radiation Mode Response



b) Structural Mode Response

Figure 3-28 Illustration of radiation and structural mode responses

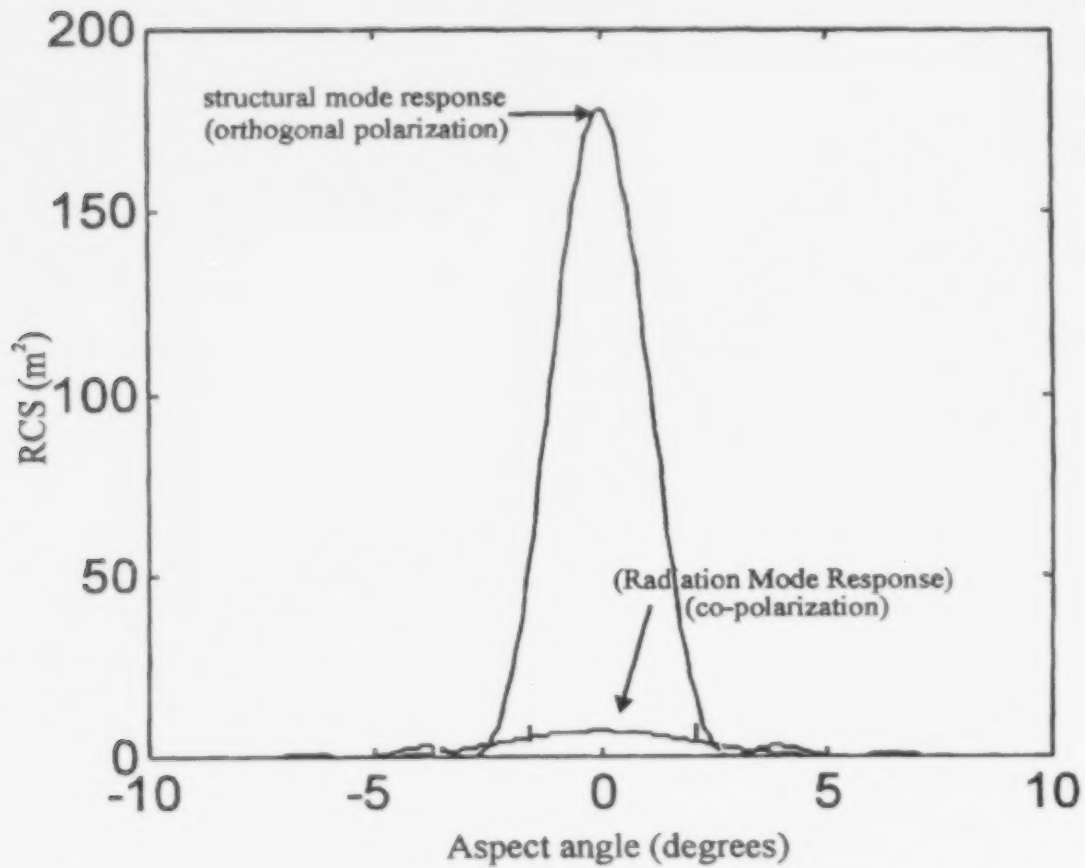
The biscattering effect is illustrated in figure b. In this case, the angle of reflection equals the angle of incidence (Snell's Law). Therefore, for every degree of θ the antenna moves, the JD radar observes a power response that is equivalent to 2θ . This implies that the power drops more sharply for the structural mode reflection over the radiation mode, which is easier to measure and assess for a given antenna deflection. Unlike the radiation mode response described in equation 38, the RCS of a structural mode response increases with decreasing PLF (i.e. as the two antennas reach orthogonal polarizations). Therefore, when the $PLF=0$, the antenna is considered to be totally reflective. When the polarizations are aligned, structural mode reflections are minimized while the radiation mode increases.

Based on equation 43, the RCS of a flat plate antenna, using the same parameters as in equation 38 but with orthogonal polarizations between the JD radar and seeker antenna, is approximately 132 m^2 . The orthogonal polarization effectively yields an antenna resembling a metallic disk, with the assumption the aperture efficiency is 1 since the illumination is uniform over the entire antenna. This is different from the radiation mode response, where the electromagnetic wave is being re-radiated by the seeker's feed horn, which is designed for typical aperture efficiencies of 60% to reduce sidelobe levels [skolnik].

A set of graphs has been produced, based on the above equations, to provide insight into the approximate power levels expected for radar signal reflections off typical anti-ship missile antennas. Note that these calculations assume a flat plate antenna configuration, ignoring secondary reflections occurring off the radome and support structures. A more rigorous treatment of the problem is required to provide exact answers regarding expected power responses of signals reflected off antennas for a specific jog detector radar.

For the following graphs, the power levels are based on peak readings, as opposed to average levels, for each pulse. No attempt has been made to relate these levels to the S/N requirements of the receiver to meet the detection criterion. Several factors have to be considered, such as bandwidth of the RF and IF receiver of the radar, temperature noise, integration factor, integration period, duty cycle, doppler tracking bandwidth, propagation factor, scintillation, doppler spreading due to multipath, etc. It is obvious that many elements come into play in deriving the precise power level received at each pulse. The graphs, nevertheless, provide a rough estimate of what can be expected, and points the way ahead for future work in this area.

The first graph, figure 3-29, illustrates the estimated radar cross section of a circular aperture antenna with a radius of 0.2 m, for both the radiation and structural mode responses. Note that the polarization alignments are different for each mode to yield maximum RCS for each case - 0° for the radiation mode, and 90° for the structural mode. The RCS is taken over an azimuth sector of ± 10 degrees. The reflection coefficient of the seeker antenna is 0.333. As expected, both responses provide maximum reflections at boresight, dropping quickly off boresight. It is observed, however, the structural mode response decreases twice as fast as the radiation mode response, as discussed. The structural mode response provides a significantly higher RCS than the radiation mode at boresight, as expected. It is clear, from this graph, that reflections due to



λ	ψ_r	θ (deg)	ρ	a (m)	f (GHz)	G (JD radar)	P_t (kw)	R (km)
.033 m	0, 90	-10-10	0.333	0.2	9	1000	100	-

Figure 3-29 Structural and radiation mode responses for circular aperture antenna

structural mode responses provide the best returns for effectiveness assessment, as long as the polarization of the JD radar is orthogonal to the seeker's antenna. Other structural reflections may change the response, however, it is not expected to make an appreciable difference, given the flat plate of the antenna is the dominant scatterer.

The next graph, figure 3-30, depicts the structural mode response power levels at the JD radar receiver for different ranges of the missile over a -10 to 10 degree aspect angle. At 10 km, the power is estimated at -60 dBm, while at 30 km, the received power is approximately -80 dBm when the seeker is boresighted to the JD radar. Clearly, at these operational ranges of the missile, the concept of using radar reflections to detect jogs appears viable, since typical radar receiver sensitivities are on the order of -100 dBm.

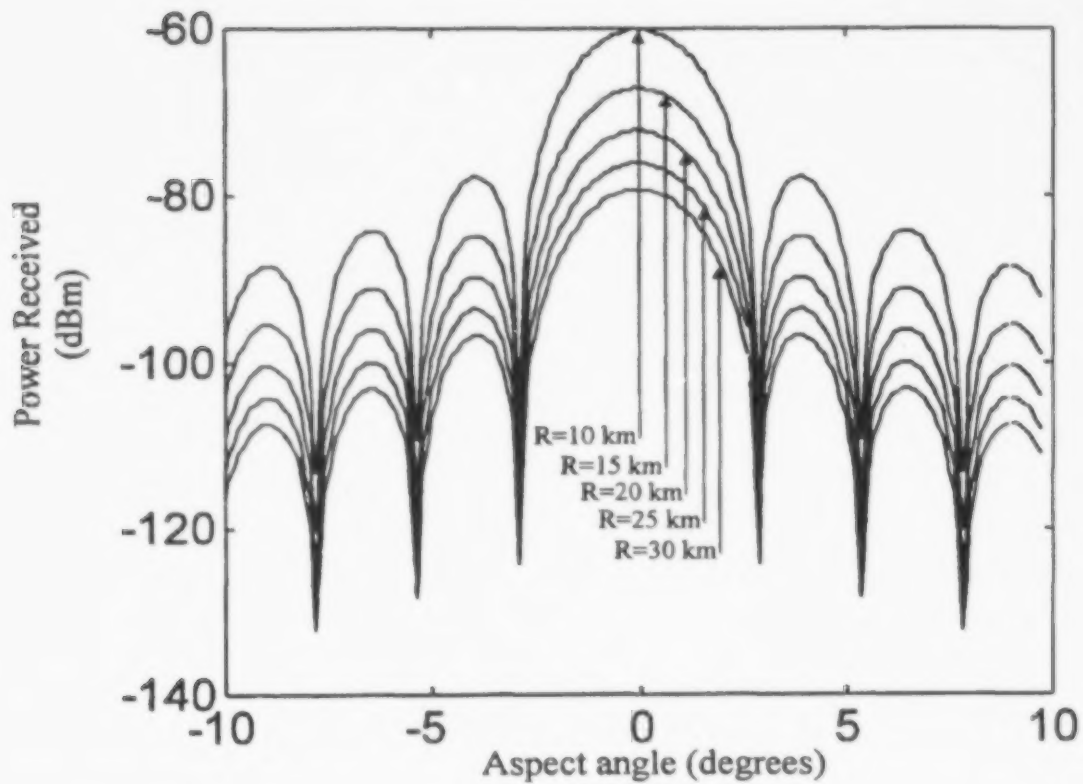
Figure 3-31 depicts the received power from seeker antenna reflections for frequencies of 3, 9, and 12 GHz to illustrate the frequency dependency of structural mode scattering. As seen, higher frequencies yield greater power levels in the echo returns and narrower half power beamwidths. Hence, it is advantageous to operate the JD radar at higher frequencies, to detect the jog more easily. However, this is offset by the disadvantages of operating at higher frequencies such as atmospheric attenuation, etc.

Based on this review, there appears to be merit in using antenna reflections to achieve jog detection. The algorithms indicate that maximum reflection occurs when the JD radar's antenna is orthogonally polarized with that of the seeker antenna, and/or when the JD radar is transmitting out of the seeker's frequency bandwidth. Both conditions give rise to a strong structural mode response, which is better for effectiveness assessment, as the associated backscattering causes the power response of the reflected energy to drop more quickly for a given jog. Furthermore, more energy is reflected back, as little or none is actually absorbed by the antenna. A strong advantage in using an active radar to measure the jog event, is that the radar parameters can be varied to minimize the effects of multipath.

One potential problem with this technique is the radar may actually serve to beacon missiles or provide a strong signal to the enemy's targeting platform. Also, this technique cannot be used during EMCON periods. Finally, this technique is ineffective against missiles which purposely slant their antennas away from target boresight, using a phased array to electrically steer the mainbeam towards the ship.

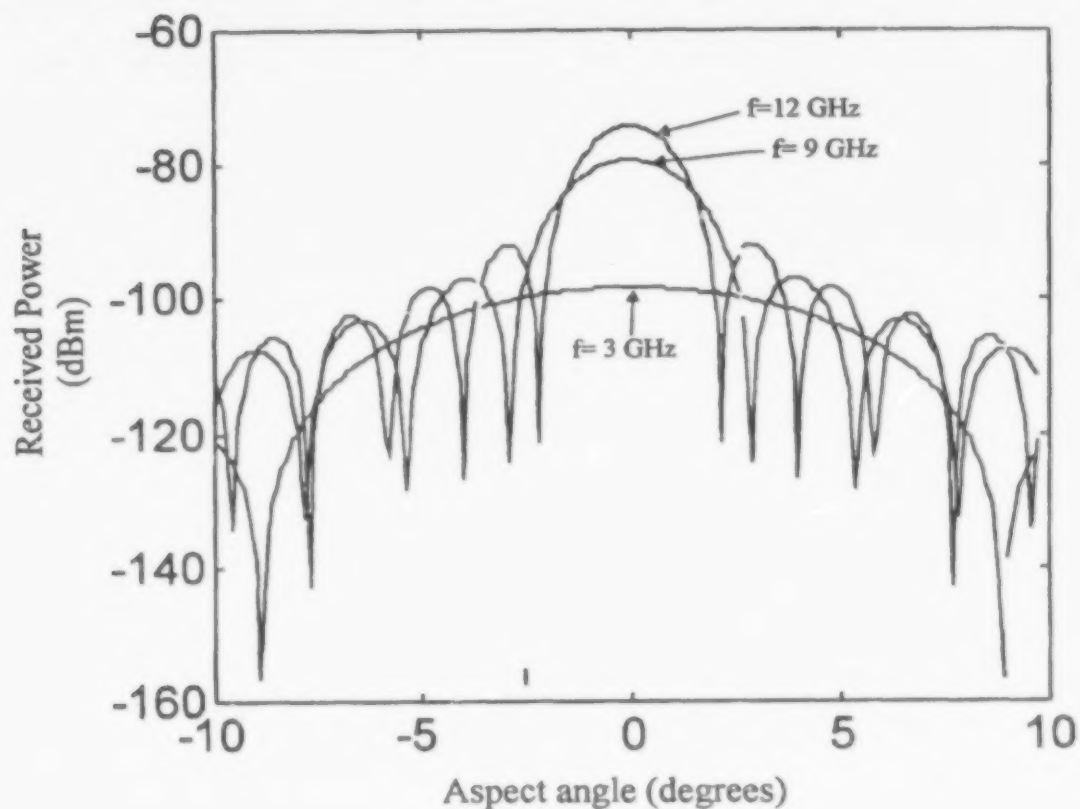
References

- [1] *Antenna Radar Cross Section*, Daniel F. Yaw, Microwave Journal, Sept 1984
- [2] *Introduction to Electronic Warfare*, D. Curtis Schleher, 1986
- [3] *Antenna Theory Analysis and Design*, Balanis. C., 1982
- [4] *Relationship between antennas as scatterers and as radiators*, R.C. Hansen, IEEE, May 1989.



λ	ψ	θ (deg)	ρ	a (m)	f (GHz)	G (JD radar)	P_t (kw)	R (km)
.033 m	90	-10-10	0.333	0.2	9	1000	100	10-30

Figure 3-30 Structural mode response for different ranges vs aspect angle



λ	ψ_r	θ (deg)	ρ	a (m)	f (GHz)	G (JD radar)	P_t (kw)	R (km)
.033 m	90	-10-10	0.333	0.2	3,9,12	1000	100	30

Figure 3-31 Structural mode response for different frequencies vs aspect angle

3.3.2 X-pol/Co-pol variations

Crosspolar jog detection involves measuring and comparing the copolar and crosspolar signals received from the radar. The underlying principle is that the ratio of crosspol to copol differs as the antenna jogs, providing a potential means of measuring jog events. Consequently, the relative characteristics of copolar and crosspolar antenna patterns are important in determining the practicality of the crosspolar jog detector.

Typical copolar and crosspolar antenna patterns of a paraboloidal reflector antenna are presented in figure 3-32 (refer to annex A for a derivation of the equations). The copolar pattern is characterized by a large main lobe centred near the mechanical boresight of the radar antenna. The crosspolar pattern is characterized by four principal lobes called condon lobes, each located in one quadrant and displaced from the antenna boresight along a diagonal. The crosspolar pattern has a deep null on boresight, with a rapid rise in gain off boresight along either principal diagonal. The crosspolar jog detector involves measuring the ratio of copolar to crosspolar power received from the radar antenna, during an engagement. Because the angular shape of the two patterns are different, the variation of the ratio of crosspolar to copolar energy is a strong function of observation angle - much stronger than the variation of the copolar antenna pattern with observation angle. This suggests that the ratio might be used to detect relatively small fluctuations of radar antenna pointing direction, and hence perform jog detection with a higher SNR than is possible by using copolar signal measurements alone. The near-boresight copolar and crosspolar antenna gains are thus important in determining the response of the crosspolar jog detector to small angle deflections of the radar antenna.

Principal cuts of the copolar and crosspolar antenna responses are presented in figure 3-33. Azimuth and elevation cuts of the copolar pattern are presented, as well as a diagonal cut of the crosspolar pattern (recall that main lobes of the crosspolar pattern lie on diagonals relative to the azimuth and elevation cuts). In this example, the copolar elevation half power beamwidth (HPBW) is slightly larger (4.0 deg) than the azimuth HPBW (3.5 deg). The peak gain of the crosspolar pattern is much lower than the peak gain of the copolar antenna pattern - approximately -20 dB below the peak gain of the copolar pattern. The relative gain of copolar and crosspolar antenna patterns is dependent on such factors as:

- (i) the antenna type (eg. front- or rear-fed paraboloidal reflector, Cassegrain, inverse Cassegrain, polarization twist Cassegrain, flat plate array, etc.)
- (ii) design parameters of the antenna (eg. ratio of focal length to diameter (reflector), mechanical design tolerances, aperture blockage effects, etc.)
- (iii) radome shape, material, and design, and
- (iv) antenna feed characteristics (reflector types) or slot characteristics (flat plate array)

A peak-to-peak isolation of -20 dB is expected for most missile antenna/radome combinations. A radome is not included in the calculations which produced the example antenna patterns presented here and referred to in the following discussion. Note also that the gain of the

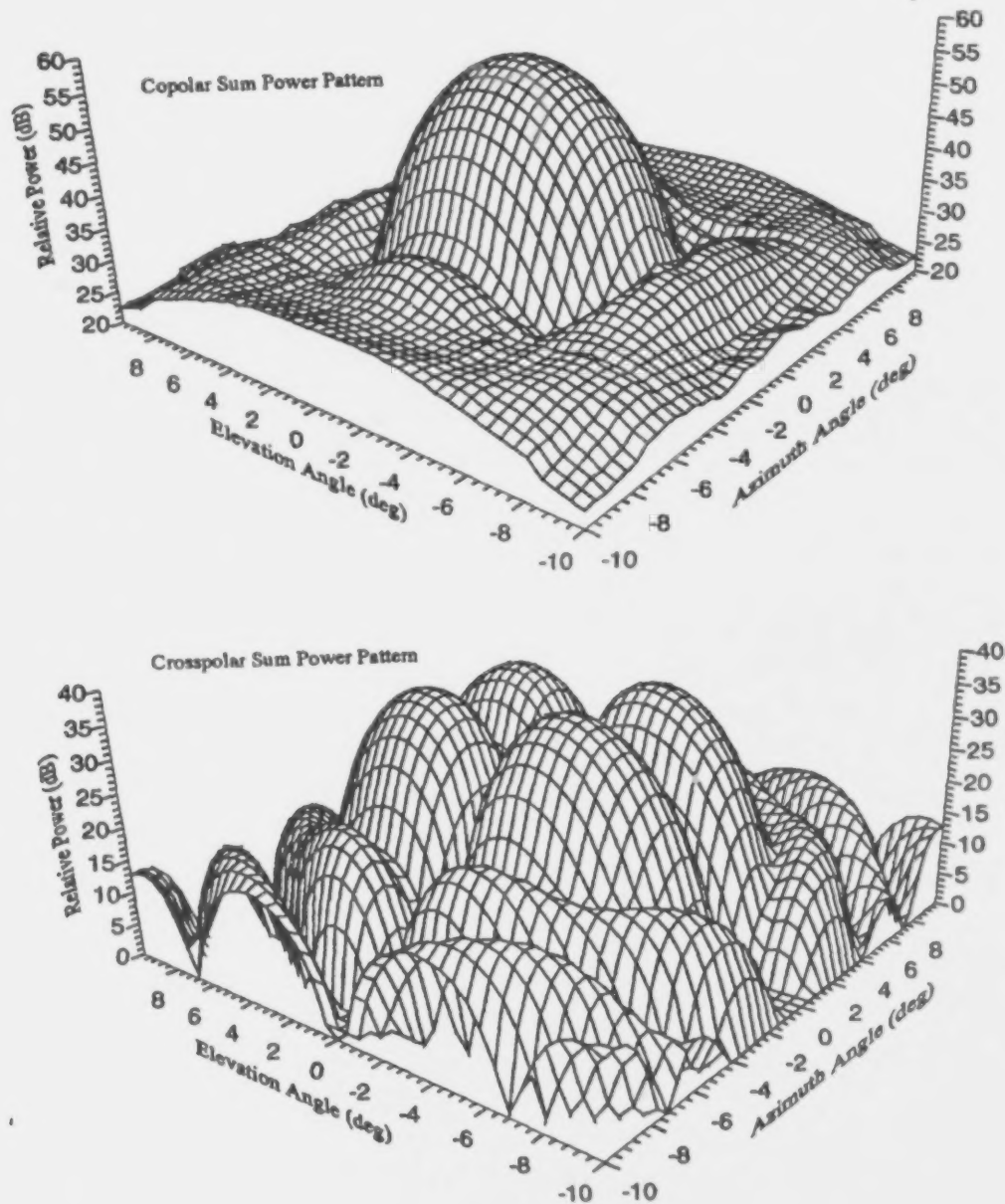
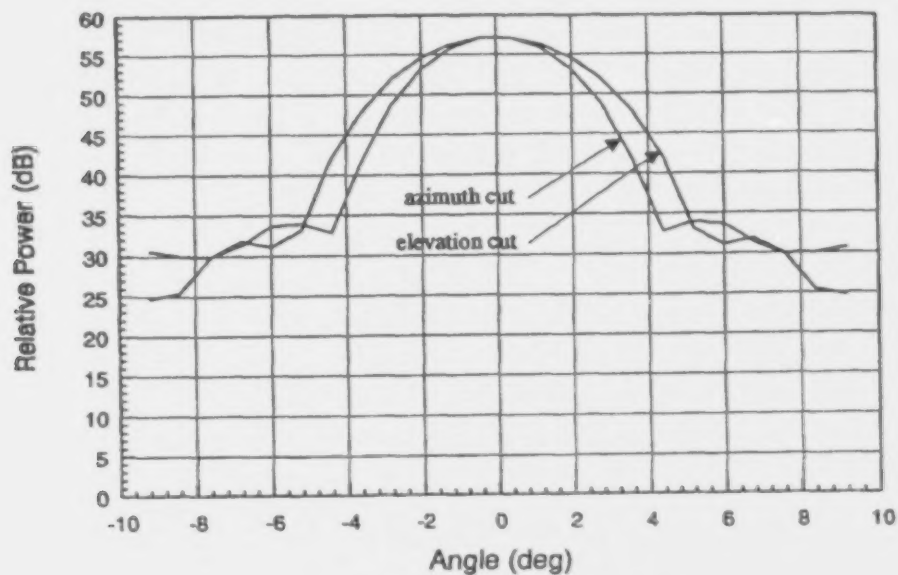
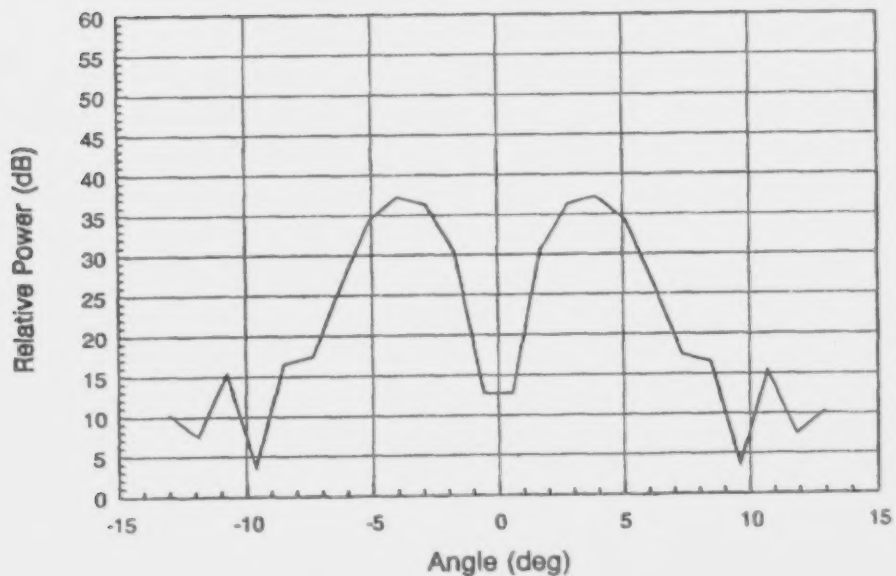


Figure 3-32 Typical copolar/crosspolar antenna responses of a paraboloidal reflector antenna



Copolar sum patterns, principal cuts



Crosspolar sum pattern, diagonal cut

Figure 3-33 Principal cuts of the copolar and crosspolar antenna patterns

crosspolar pattern changes rapidly as the angle of observation moves off antenna boresight, and that the gain of the pattern near boresight is much lower than the gain of the copolar pattern measured near boresight. In this example, the near-boresight crosspolar antenna gain is more than -45 dB below the near-boresight copolar antenna gain (exact gain at boresight is not shown in figure 3-33 due to angle quantization of data). The exact gain of the crosspolar pattern near boresight is determined by a number of parameters involving both mechanical and electrical tolerances achieved by the antenna designers and manufacturers, including reflector shape, hybrid performance in the monopulse comparator (monopulse radar), feed distribution characteristics, etc. In any case, because the near-boresight isolation between copolar and crosspolar radar antenna patterns is so great, the overall performance of the jog detector system is expected to be sensitive to the alignment of the crosspolar JD antenna with the crosspol of the radar antenna.

An example is now presented to illustrate the possible performance of a crosspolar jog detector, in the absence of multipath effects. Although the conditions represented in the simulation are artificial, the results serve as a necessary quantitative departure point for a more complete and comprehensive analysis.

In this example, a hypothetical missile radar is subjected to swept Crosspol jamming. The characteristics of the radar and jammer are:

Type: three channel monopulse with AGC; home-on-jam mode represented
Antenna: rear-fed paraboloidal reflector, 25 inch diameter, 10.5 inch focal length
Comparator: nonideal, randomly distributed phase and amplitude errors throughout the network, bounded by estimated achievable electrical tolerances
phase errors at ports 1, 2, Σ , Δ : random over ± 3 deg
amplitude errors at ports 1, 2, Σ , Δ : random from 0 dB to -0.3 dB
post-comparator errors ($\Sigma, \Delta_{\Sigma}, \Delta_{\Delta}$): (0.0 deg, -0.2 dB, -0.4 dB)

Angle Tracking: Type I servo loop, rate commanded

Azimuth:	natural frequency:	1.5 Hz
	damping ratio:	1.0 (unitless)
	gain constant:	0.0406 rad/sec/volt
Elevation:	natural frequency:	1.0 Hz
	damping ratio:	0.9 (unitless)
	gain constant:	0.0281 rad/sec/volt

AGC: Type 0 servo loop

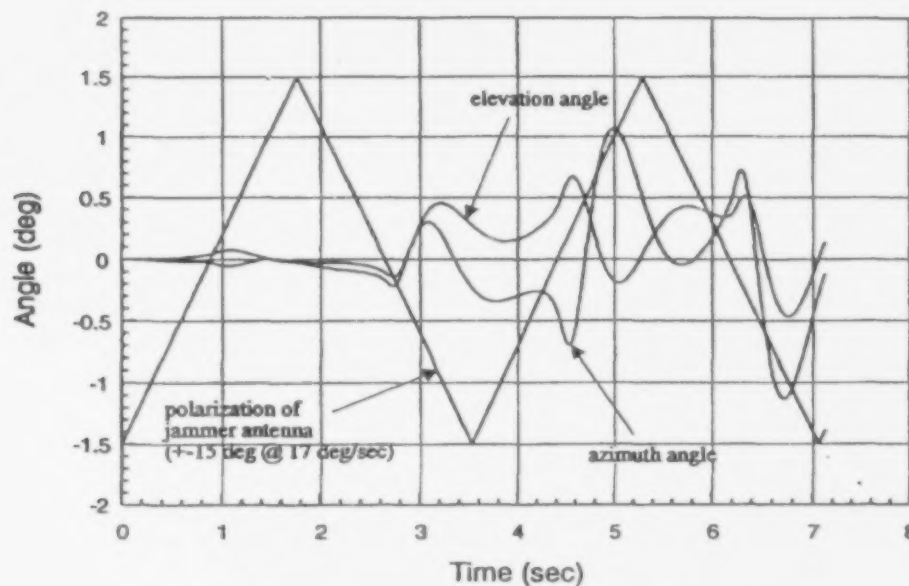
natural frequency:	15 Hz
damping ratio:	0.9 (unitless)
gain constant:	1.0

Jammer: linearly polarized, variable sweep rates and limits

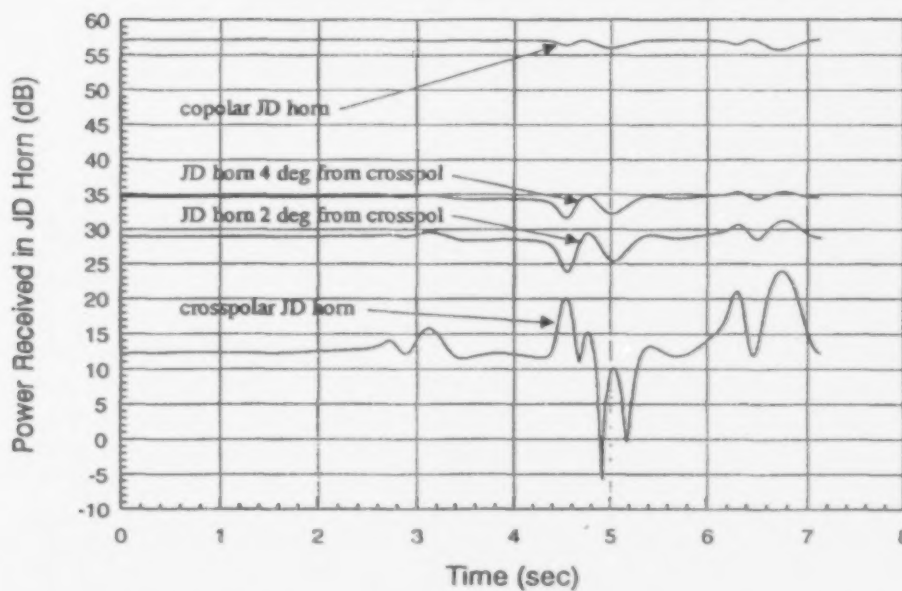
The radar and jammer models described above were used in a simulation of swept Crosspol jamming. The simulated angle behaviour of the radar is presented in figure 3-34 along with the power calculated in the copolar and crosspolar antennas of the crosspolar jog detector system. In this case, the jamming produces relatively small deflections of the radar antenna in angle - of the order of ± 1 deg. The signal received in the copolar jog detector (JD) horn shows very small fluctuations - of the order of ± 1 dB. The dynamic range of fluctuations in the signal received by the crosspolar horn is of the order of 25 dB, though much lower power is received as compared to the copolar JD horn. If the crosspolar horn is misaligned by 2 deg or 4 deg, the received power increases, and the dynamic range of the signal fluctuations is reduced, but still greater than that of the signal in the copolar horn (3 - 5 dB vs. 1 dB). The simulated performance of the jog detector is presented in figure 3-35, where the crosspolar signal levels shown in figure 3-34 are normalized to the copolar signals. These curves are similar to the crosspolar power curves presented in figure 3-34, because the copolar signal levels exhibit very little fluctuation due to the small angle deflections of the radar antenna.

The simulation was repeated for jammer sweep rates and limits chosen to produce large angle errors in the radar. Results are presented in figure 3-36. Large fluctuations in received power are shown for both copolar and crosspolar JD horns, though as expected, large copolar signal variations are only associated with large angle errors in the radar. The performance of the jog detector for this simulation is presented in figure 3-37. The dynamic range of the signal from the JD is dependent on the alignment of the crosspolar horn, but in this example ranges from approximately 55 dB (crosspolar JD horn aligned with radar crosspol) to approximately 35 dB (crosspolar JD horn aligned 4 deg. from radar crosspol). However, the signal in the copolar JD horn also shows significant dynamic range in the case of large angle deflection of the radar - of the order of 35 dB.

The results of these two simulation examples, considered together, illustrate some key issues to be addressed concerning the practicality of a crosspolar jog detection scheme. In the first example, it appears that a crosspolar JD system can, in the absence of multipath effects, be used to sense small angle disturbances in a tracking radar, provided that the signal is large enough to be detected and provided that the crosspolar JD antenna is properly aligned with the crosspol of the radar. In this simple simulation, a copolar JD system does not have comparable sensitivity. In the case of large angle errors in the radar tracking performance, both the copolar and crosspolar JD approaches exhibit good performance - this is because, unlike small antenna deflections, large deflections cause large fluctuations in both copolar and crosspolar signal levels. In the case of large angle deflections, the x-pol/co-pol ratio could help discriminate against signal fluctuations attributed to multipath. To indicate the true usefulness of the crosspolar approach, a comparative measure of effectiveness (MOE) is required to meaningfully compare the

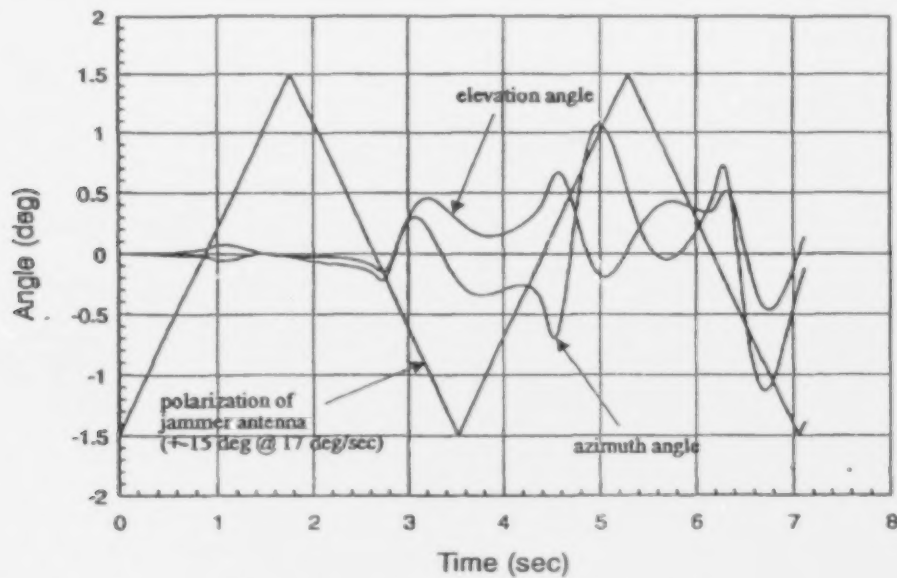


Radar antenna scan angle vs. time, swept Crosspol jamming

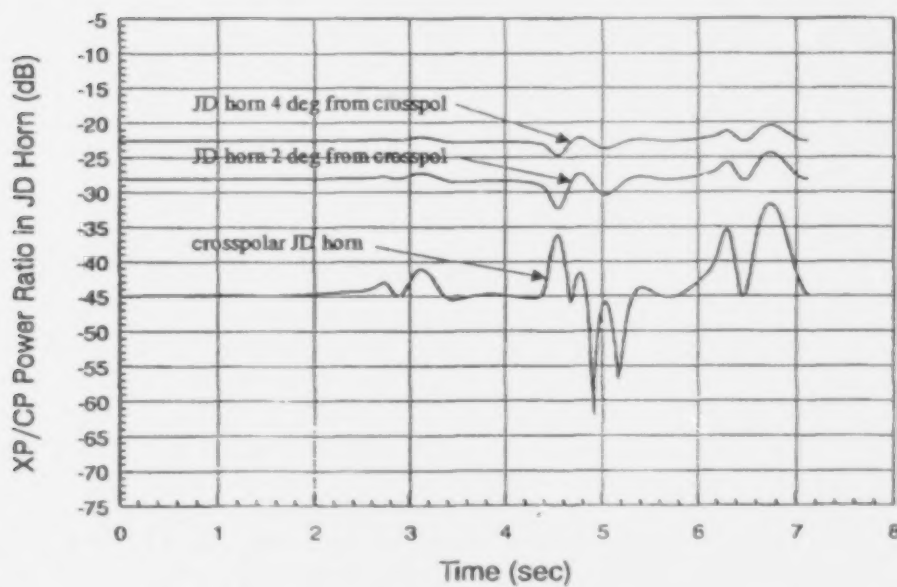


Power received in jog detector horns vs. time, swept Crosspol jamming (multipath not modelled)

Figure 3-34 Simulated co-pol/X-pol signals, swept X-pol inducing small radar angle errors

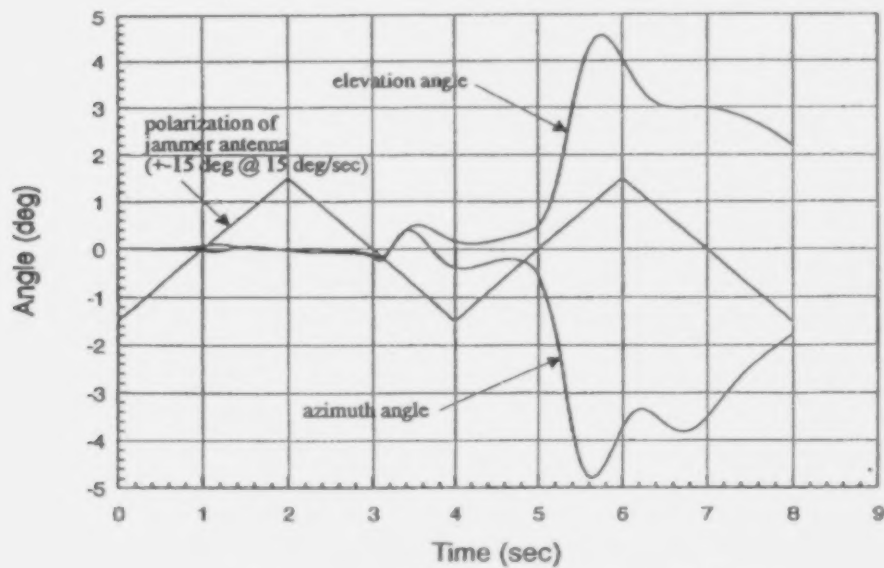


Radar antenna scan angle vs. time, swept Crosspol jamming

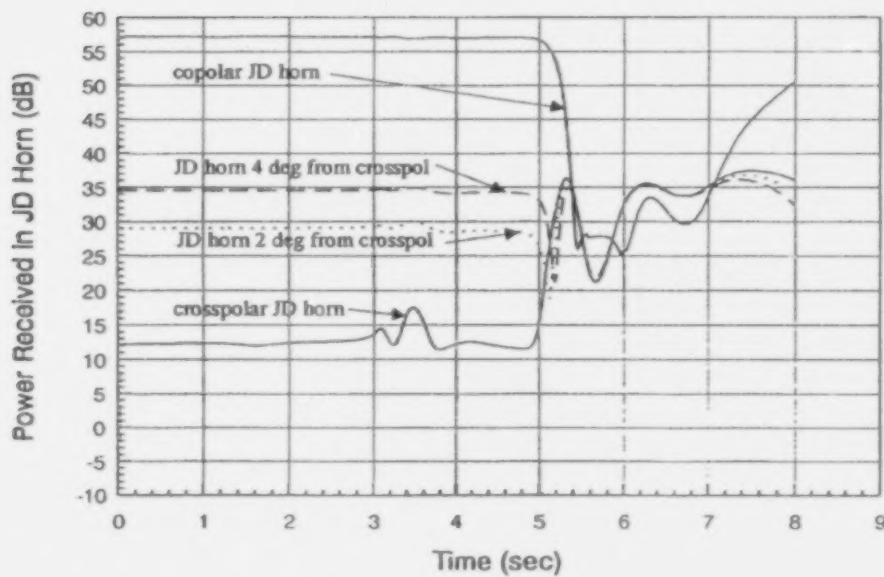


Ratio of crosspolar to copolar power in jog detector horn vs. time, swept Crosspol jamming

Figure 3-35 Simulated jog detector, swept X-pol inducing small angle errors

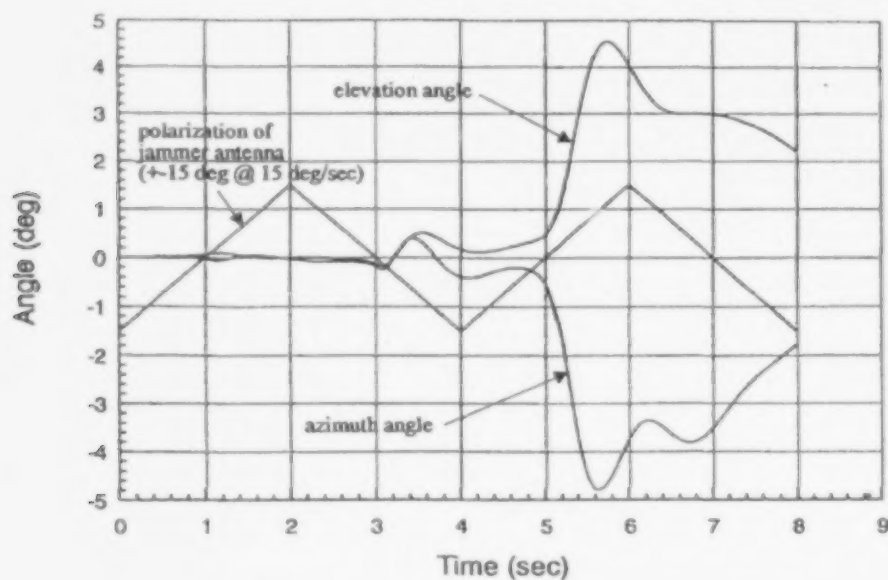


Radar antenna scan angle vs. time, swept Crosspol jamming

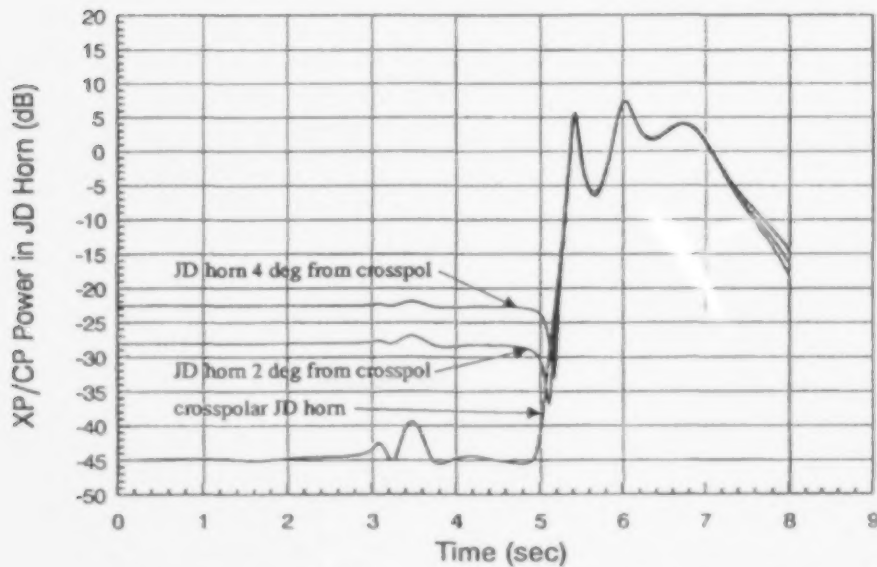


Power received in jog detector horn vs. time, swept Crosspol jamming

Figure 3-36 Simulated co-pol/X-pol signals, swept X-pol inducing large radar angle errors



Radar antenna scan angle vs. time, swept Crosspol jamming



Ratio of crosspolar to copolar power in jog detector horn vs. time, swept Crosspol jamming

Figure 3-37 Simulated jog detector, swept X-pol inducing large radar angle errors

performance of the two approaches. A heuristic MOE might be a calculation of the differences in dynamic range between the two approaches. Such a MOE could be used to quantitatively estimate the advantages of the crosspolar JD approach, normalized to the performance of the less complex and less sensitive copolar approach.

Further insight into the performance of a crosspolar JD system may be gained by plotting a special type of radar antenna pattern, consisting of the crosspolar radiation pattern normalized to the copolar pattern (see figure 3-38). Such a pattern indicates the signal produced by the crosspolar JD system as a function of radar antenna scan angle (in the absence of multipath). Contours could then be plotted on this surface, indicating the expected dynamic range of the signal from the crosspolar JD system as a function of antenna scan angle, again in the absence of multipath. Repeating this type of calculation for several types of radar antenna (ie. for several relative copol/crosspol pattern levels) could give an indication of the robustness of the crosspolar JD approach to different crosspol levels in the threat radar.

An important consideration in determining the practicality of such a jog detection system in the required system sensitivity of the crosspolar JD system. This is a particularly sensitive issue for this scheme because the crosspolar signal from the radar antenna may be much lower than the copolar signal, particularly if the host platform is being accurately tracked in angle by the missile (i.e. if the jog detector antenna is on or very nearly on the line of sight of the radar antenna). As noted previously, digital modelling suggests that although the condon lobes of the missile antenna may be expected to be -20 dB to -30 dB below the peak copolar signal level, the near-boresight missile crosspolar antenna response may be -40 dB (or even less) below the boresight copolar response. The jog detector system must thus have sufficient sensitivity to detect the residual crosspolar signal near the boresight of the missile antenna. The required system sensitivity may be estimated by calculating the crosspolar signal received by the crosspolar JD system.

The Friis Transmission equation may be used to estimate signal received by the jog detection system from an inbound missile. It is expressed [1] as:

$$P_r = \frac{\lambda^2 P_t G_{\alpha} G_{\sigma}}{(4\pi R)^2} \quad (44)$$

where

P_r = power received at jog detector antenna
 λ = radar wavelength
 P_t = transmitter power of missile
 G_{α} = gain of missile antenna
 G_{σ} = gain of jog detector antenna

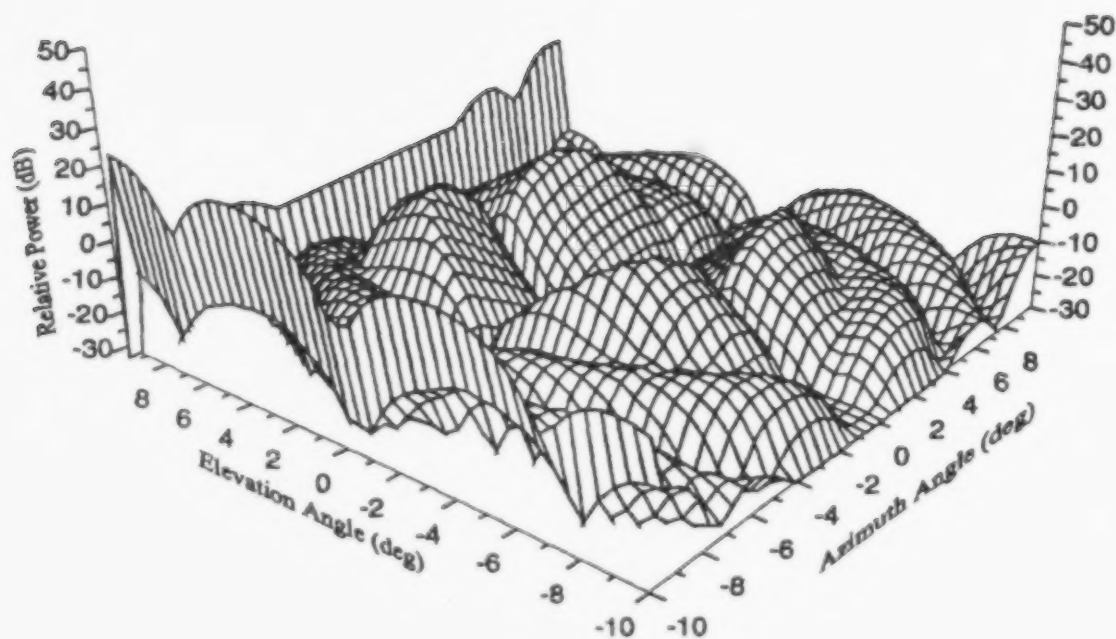


Figure 3-38 Crosspolar radar antenna pattern normalized to copolar pattern

R = range between the jammer and radar

The following parameters are used in an example calculation:

P_r = to be calculated
 λ = 3.333 cm (9.0 GHz)
 P_t = 100 kW = 80 dBm
 G_{ot} = 32 dBi
 G_{or} = 10 dBi
 R = 30 km

Using the Friis transmission equation above, the copolar signal received at the jog detector (assuming perfect polarization matching between missile and jog detector antennas) is -19 dBm. If the crosspolar signal near boresight of the missile antenna is -40 dB below the copolar signal, the minimum required system sensitivity is approximately -60 dBm or better. The useful system sensitivity may be bounded at approximately -40 dBm in this example, assuming that the maximum crosspolar signal is approximately -20 dB below the maximum copolar signal. This means that if the minimum detectable signal by the system is higher than -40 dBm, the crosspolar signal from the missile cannot be detected at a range of 30 km regardless of the missile antenna deflection angle.

Multipath effects are a major factor in assessing the practicality of a crosspolar JD system. Consideration of these effects is beyond the scope of this overview, except to note that low angle copolar scatter from the sea surface may be expected to be different than low angle crosspolar scatter. Detailed analysis is required to estimate SNR and overall system performance in the presence of multipath. A method is required to filter signal fluctuations due to multipath from signal fluctuations due to radar antenna movement in response to jamming. There are a number of possibilities here, including (but not limited to) the use of spatial diversity in the JD antenna assembly, continuous correlation of suspected jogs with jamming activities, and simultaneous comparison of signal fluctuations between copolar and crosspolar channels of the jog detector.

3.3.3 Amplitude Changes

This section describes a method for achieving jog detection based on measuring power fluctuations in the received signal from anti-ship missiles. Two implementations are discussed, one using a single antenna, and the other utilizing multiple antennas aligned in a vertical array configuration.

3.3.3.1 Single Antenna

Jog detection can be realized by measuring the power decay rate of the signal received from a seeker as its antenna deflects from the ship's line of sight (LOS). This method is currently implemented in the RAMSES jammer. In general, the hardware configuration required to achieve

this type of measurement is relatively straightforward, comprising essentially a single antenna, such as a horn, and a receiver with sufficient sensitivity and resolution to detect and resolve signal fades associated with the jog event.

The received power level from a seeker is calculated as,

$$P_{rec} = \frac{P_t G_t A_r}{4\pi R^2} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \quad (45)$$

where,

P_t = seeker transmit power

G_t = seeker antenna gain

A_r = effective aperture of JD antenna

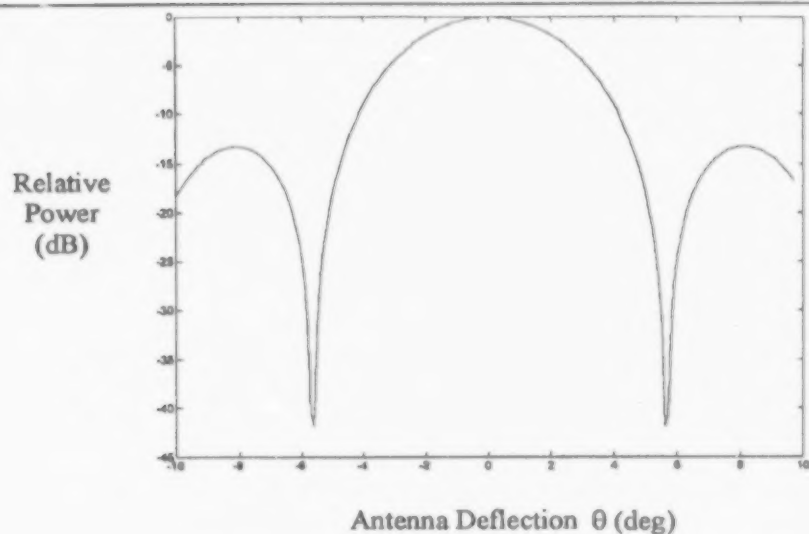
G_r = gain of JD antenna

R = radial range between JD antenna and seeker antenna.

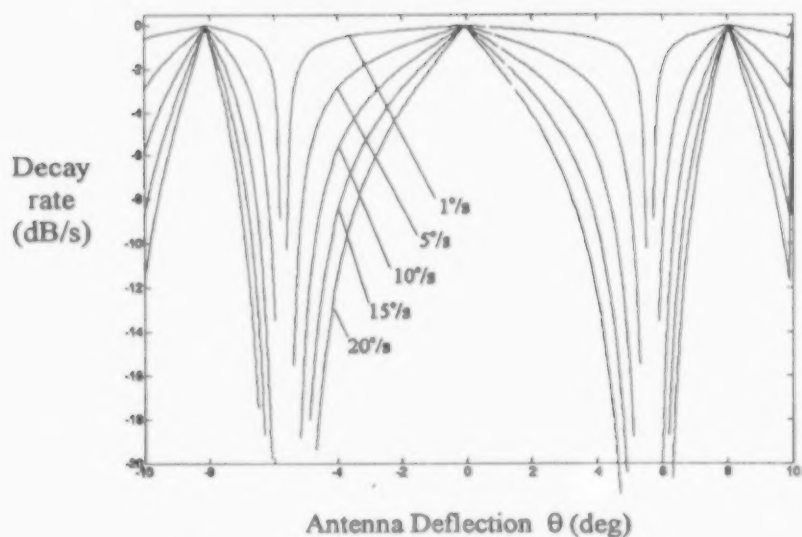
Assuming a typical transmit power level of 100 kw, a gain of 30 dB for both antennas, and a wavelength of 3 cm, the received power level would be -62 dBm at a missile range of 30 km from own ship. Given a typical receiver sensitivity level of -65 dBm, for a wide bandwidth ESM type receiver, or -100 dBm for a matched receiver, the jog detector would have no difficulty in detecting the signal. However, measuring the actual decay rate might be more difficult, not due to the dynamics (resolution) of the jog detector receiver, but to the seeker's transmit antenna pattern.

Since the jog detector measures the seeker's transmitted energy, the signal fade associated with the jog event is directly related to the size and shape of the seeker's antenna power radiation pattern. At or near boresight, the antenna pattern is relatively flat, producing minute changes in signal drop for slight jogs. It is only when the antenna deflects on the order of a half power beamwidth (HPBW) that appreciable signal level changes are observed, making it possible to detect the jog event. From a jammer/EWCP perspective, the earlier the jog event can be detected, the quicker the countermeasures can be refined to ensure optimal jamming.

In the absence of propagation anomalies, the characteristics of a measured signal decay is based on the seeker antenna's HPBW, rate of angular swing and the extent of the antenna deflection. Figure 3-39 illustrates the types of instantaneous decay rates that can be theoretically measured for a rectangular aperture antenna with a 5 degree HPBW versus different angle deflection rates. As shown, at lower deflection rates, 1-5 °/s, there is little change in measured power levels except when the antenna approaches a full beamwidth swing in one direction. At higher deflection rates, beyond 10°/s, the power decay rates are much more pronounced. From [2], typical jog rates can vary anywhere from 0 to 20°/s, with the upper limit governed by the maximum slew rate of the antenna servos.



a) Antenna Pattern



b) Instantaneous decay rates of a 5° HPBW antenna for different deflection rates.

Figure 3-39 Instantaneous decay rates of a 5°HPBW antenna for different deflection rates

To further illustrate the variations of jogs, figure 3-40 depicts the received power decay rates for antenna HPBW's of 3, 5, and 10 degrees, all deflecting at a rate of 15 deg/s. As shown, narrower antenna beamwidths produce the greatest decay rates in the shortest period of time, which is desirable for jamming effectiveness assessment. Typical antenna power beamwidths for anti-ship missiles fall in the 3-5° range.

The above decay rates are based on the instantaneous decay rate (i.e. first order derivative with respect to scan angle) of the seeker antenna multiplied by its angular velocity. Since the instantaneous rate is dependent upon the shape of the antenna radiation pattern, the decay rate varies with antenna scan angle (this is illustrated in figures 3-39 and 3-40). Hence, no single value can be used to describe the power response of a given jog. Instead, a jog fade is averaged over time - if the measured power drop rate persists for a certain amount of time and exceeds a pre-defined threshold, then a jog is declared. RAMSES uses a criteria of $<B3>$ dB/s over 0.25 seconds for a jog. Hence, if any signal decreases at a rate of or greater than $<B3>$ dB/s for no less than a quarter of a second, then a jog event is declared. A typical dynamic range for a logarithmic receiver is 60 dBs, while an AGC type receiver provides a typical range of 30 dB. Therefore, the dynamic range of the receiver is not the limiting factor in measuring jog fades.

A key factor which may limit the performance of the single antenna jog detector is propagation anomalies, particularly multipath. Multipath is defined as the propagation of an electromagnetic (EM) wave via more than one path - a direct one and indirect ones through reflections off the surface of the water [2]. Refer to figure 3-41 (a) for an illustration of the two propagating paths and the geometry involved. These signals combine vectorially at the receiver to produce fluctuations or fades in the received radar signals as the missile approaches the ship, as shown in figure 3-41(b). The potential problem with multipath, is that the resultant signal fluctuations can resemble jog fades, leading to false or ambiguous readings in jog detection. Since most anti-ship missiles fly at low altitudes, with the exception of high divers, multipath will be present, and hence, its effects are of concern to the ECM effectiveness assessment function of EWCP.

3.3.3.2 Multiple Antennas (spatial diversity)

Research was performed at the Electronic Warfare Division (EWD) at DREO to investigate the characteristics of maritime multipath, and to seek ways of overcoming its potentially disturbing effects on jog measurements. One principal feature of the anomaly examined, and eventually exploited to form the basis of a jog detection design, is that maritime multipath is a height dependent phenomenon - i.e. the power response of the received signal, due to multipath, is directly proportional to the heights of the transmitter and receiver. Fades due to jogs, on the other hand, are not height dependent. Figure 3-40 (b) depicts the relative power response of a EM wave subject to smooth surface multipath for different heights of the receive antenna. In this case, the wavelength is 0.333 m, and the height of the transmit antenna is 10 m. As indicated, the nulls occur at different ranges of the missile for each height of the receive antenna. The difference is more pronounced at far ranges, becoming less distinguishable at closer ranges (<1 km). There is actually a duality relationship between height and range regarding the profile

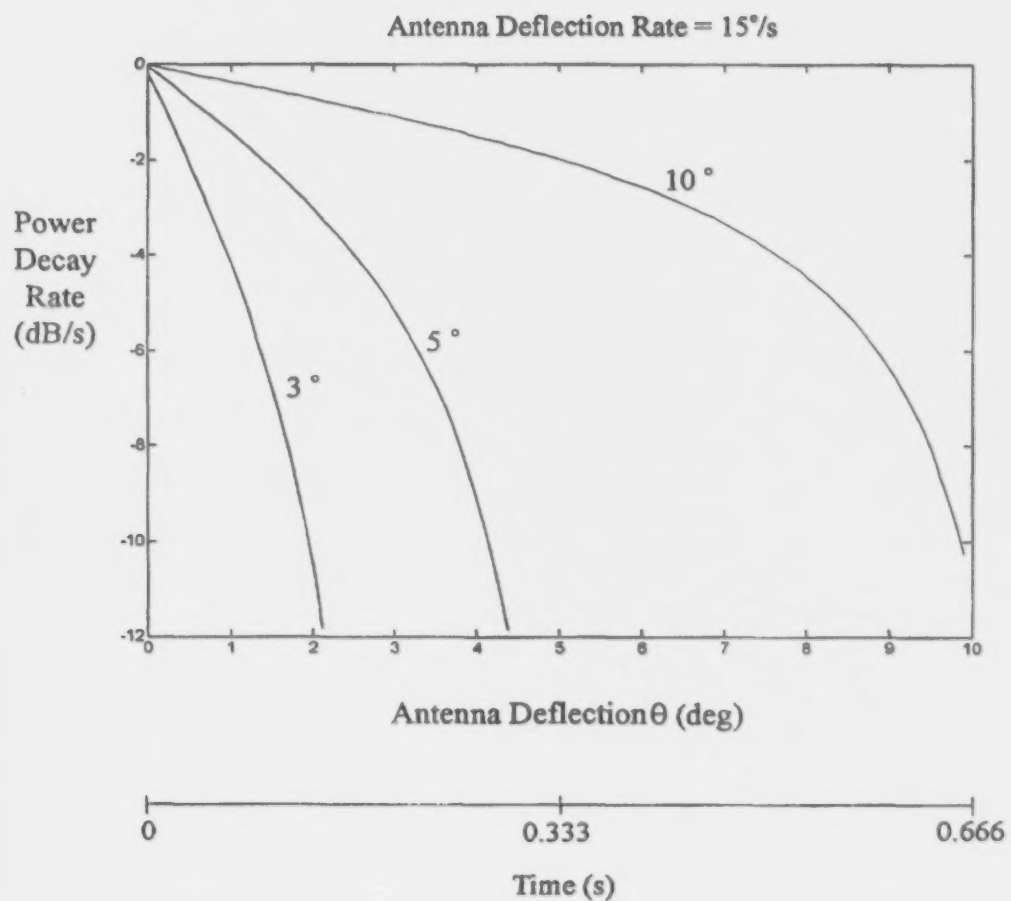
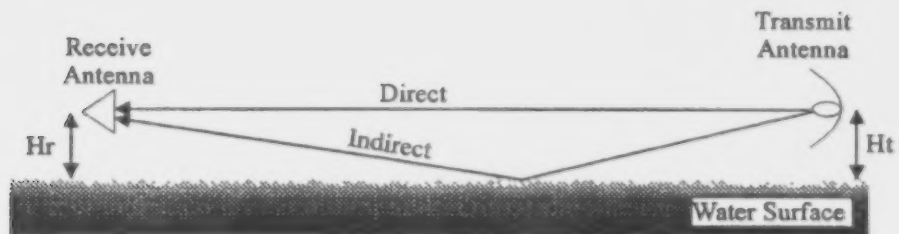
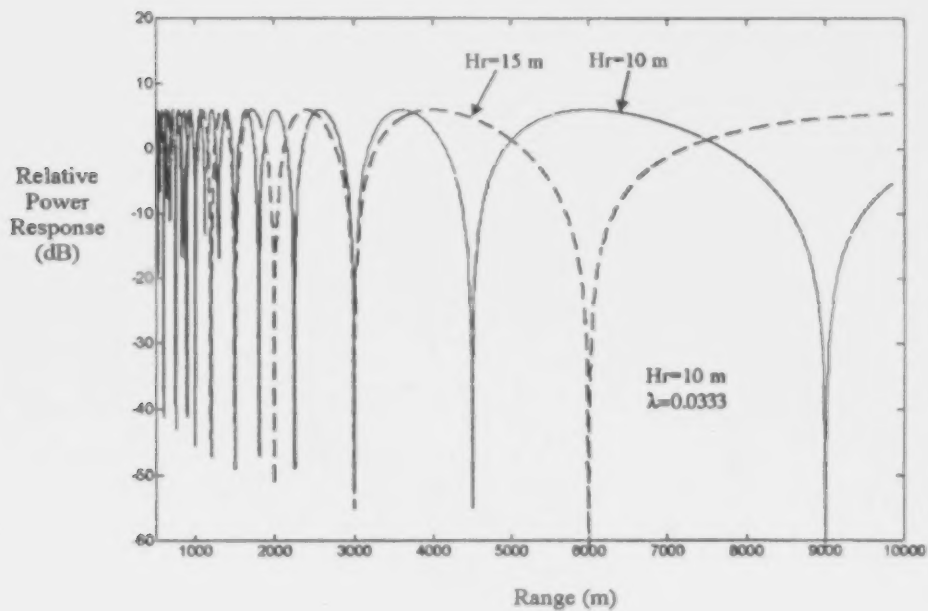


Figure 3-40 Instantaneous decay rates for a 3, 5, 10° antennas for deflection rate of $15^\circ/\text{s}$



a Smooth Surface Multipath Geometry



b) Signal Fades due to Flat Surface Multipath Effects

Figure 3-41 Multipath geometry and signal fades

of the multipath fades. A transmit antenna that is very close to the surface but far away from the receiver, produces similar multipath effects as one that is high above the surface but close to the receiver. This relationship is brought to bear when selecting the number of antennas required to resolve potential ambiguous jog readings and to determine how they should be placed along the vertical stack (i.e. determine separation between antennas).

A jog detection algorithm was established based on the height dependent principle, and is shown in figure 3-42. For a detailed description of the detector, refer to reference [2]. Within the context of this report, a brief explanation of the detector follows, with emphasis given to the application of NEWCP.

Three horns are used, placed along a vertical stack. Based on many simulation runs and analysis, it was determined that three antennas provide the best performance against a variety of multipath effects and missile geometries. As will be discussed below, this number is driven mostly by the characteristics of rough surface multipath, particularly those originating from sea swells. Each horn of the jog detector is fed to separate channels comprising a downconverter, detector/rectifier, A/D converter, differentiator, and a threshold comparator. The differentiator is used to quantify the rate of decay of the received signal. When the signal is experiencing a fade, the output of the differentiator rises, while a steady signal level or no deviation produces a zero output. Since each horn is placed at different positions along the vertical support, different multipath fades are measured due to the height dependent aspect of the anomaly. Hence, during multipath fading, it is not expected that all three horns will measure precisely the same fade, leading to a non-jog declaration. On the other hand, when a jog occurs, each horn measures the same fade, and hence, a jog is declared. The differentiator is used to measure and compare the power responses from each horn, rather than the amplitude, for the following reason: the derivative does not require *a priori* information regarding transmit power levels or range-to-go to select the appropriate threshold level. The derivative describes the jog strictly on the basis of antenna motion, no matter how close the missile is or how much power its seeker is radiating.

A minimum of three horns is required to remove any false jog readings due to the path length ambiguity measurements of the reflected signal at each horn. In other words, there are certain geometries where the reflected signal has travelled the same number of wavelengths to each horn, causing ambiguous readings. It was found that three horns provided unambiguous readings for most of the missile flight, with only minor ambiguous detections at ranges less than 1 km. However, from an EW perspective, this range is not considered critical since the hardkill systems engage the threat well before this point.

The spatial diversity approach offers some performance advantage against multipath anomalies arising from rough surfaces, particularly sea swells. Sea swells are defined as ocean waves that have travelled out of their generating area. They travel great distances, and as a result, exhibit very slow (long periods) and regular undulations, with small crests and large autocorrelation distances. They are distinguished from their smaller counterparts, called sea or capillary waves, which are characterised by very short periods and rapid fluctuations. Sea waves dissipate the

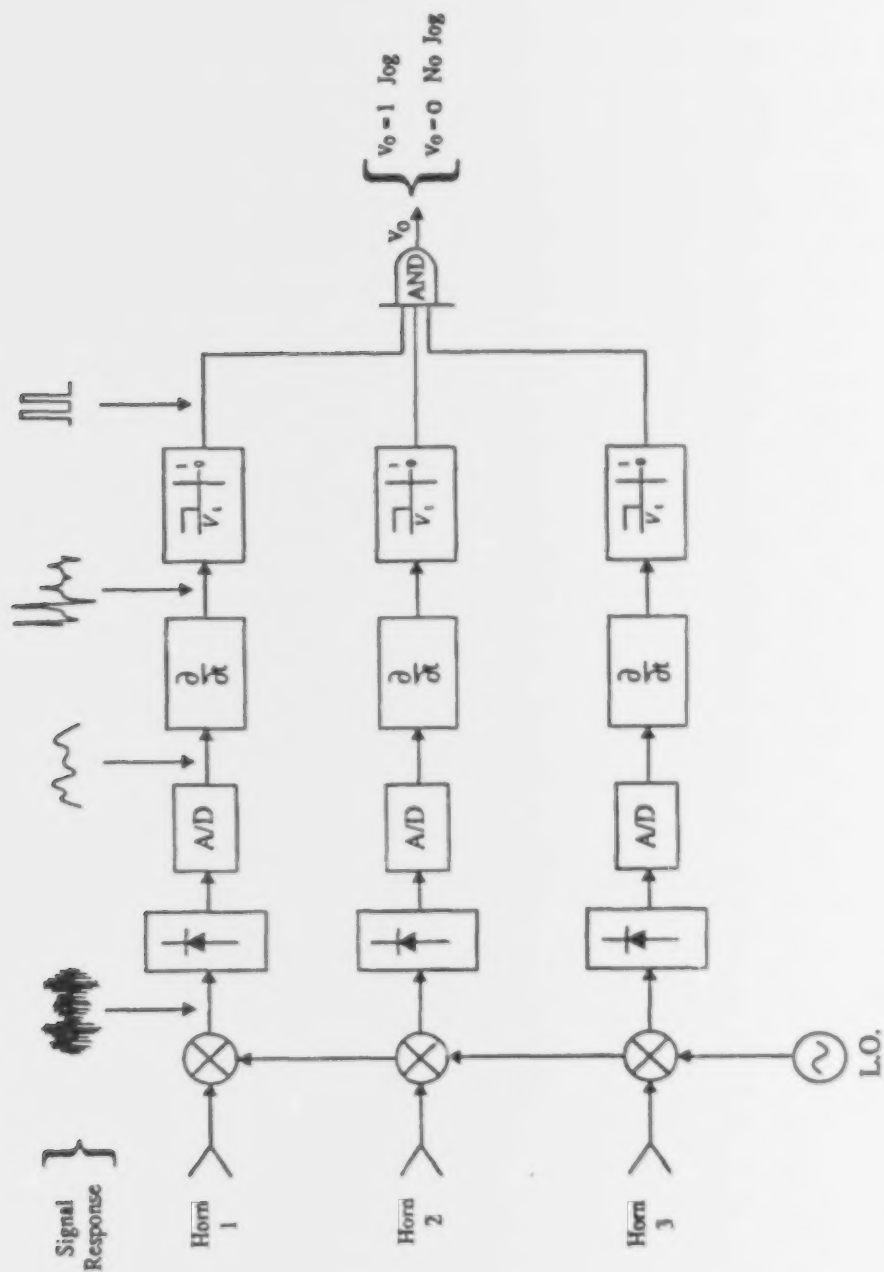


Figure 3-42 Block diagram of proposed jog detector

moment the wind dies down. The effect of sea waves is to introduce noise like interference in the power response of the received signal, which does not appear to pose a problem for the jog detector.

Since the sea swells have very slow undulations with long autocorrelation distances, they create multiple quazi-specular reflective surfaces, which can be troublesome for the jog detector. Quazi specular lies in between specular conditions, where the surface is smooth, and diffuse conditions, where the surface is rough. Note that all three components can exist simultaneously, depending upon sea state and geometry. A purely specular surface causes the signal to experience deep fades at regular intervals as the missile approaches the ship - as illustrated in figure 3-41(b). Diffuse multipath, on the other hand, tends to introduce shallow fades with rapid fluctuations, indicative of noise, which is considered to be a less of a problem for the jog detector. Quazi specular multipath causes the received signal to fluctuate both rapidly and with relatively deep nulls occurring at random intervals for a given missile profile. The characteristics of these nulls can be similar in nature to a fade expected from a jog, leading to possible false jog readings for a jog detector with a single antenna.

The extent to which multipath fades resemble jog fades for a rough sea surface is illustrated in figure 3-43. The results are based on simulation runs performed in [2]. Four graphs are shown for different sea swell wavelengths of ∞ (smooth surface), 500 m, 150 m, and 50 m. The sea swells are characterized by a r.m.s. wave height of 2 m and a period of 18 s. Jogs were introduced at ranges of 8, 6, 4, and 2 km. Each jog was represented by an antenna angular swing of 15° in one direction and back over a period of 2 s. For the smooth surface case, the jog fades are obvious. However, for sea swell wavelengths of 500 m to 150 m, the jog fades become totally concealed, making them virtually impossible to detect. At a wavelength of 50 m, the jog fades become distinguishable again, as the multipath effects become more noise-like.

Treating the jog-multipath ambiguity problem through the application of classical signal processing techniques may not be possible, since *a priori* knowledge of the characteristics of either the signal or noise is required to derive optimal algorithms. The jog fades themselves are extremely difficult to characterize, since by the very nature of jamming, they can occur randomly, at any rate, for any period of time, and produce any amplitude depth. Some informal experiments were performed at DREO to attempt to establish correlation between jamming and its effect on antenna behaviour, however, it was observed that ambiguous antenna responses existed for almost every ECM technique tested. More work is required in this area to explore and define any unique antenna characteristics which could be exploited for jog detection.

Attempting to characterize multipath effects also appears to be an elusive goal for certain sea state conditions. The treatment of the problem is relatively straightforward for smooth surfaces, using basic reflection theory to characterize the signal fades. In this case, several algorithms can be used to predict and filter out the effects of multipath including Maximum Likelihood Estimation (MLE), Kalman filtering, etc. These algorithms are most effective when the range of the missile is known, which may not be provided in this case. The complication begins when

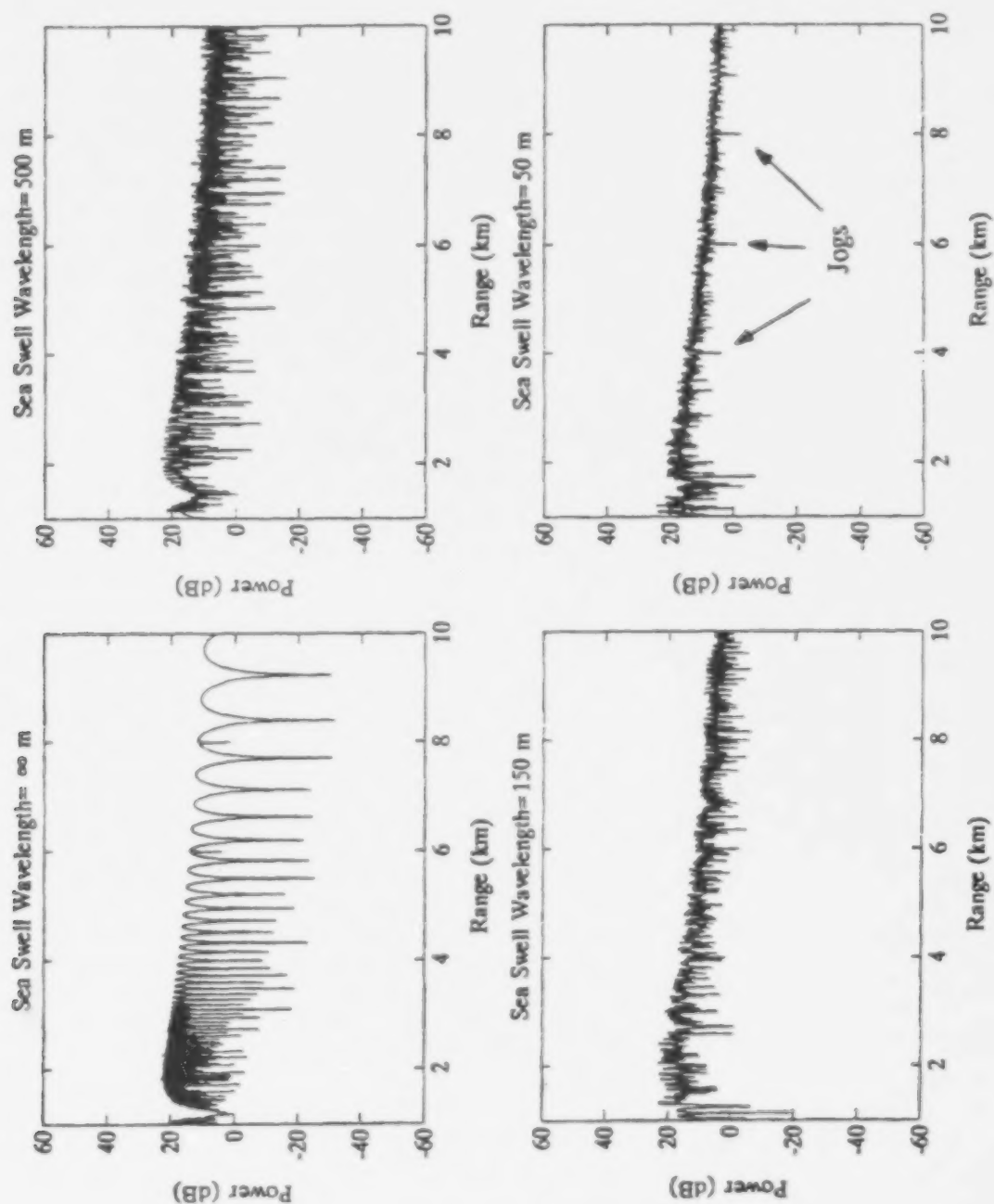


Figure 3-43 Multipath effects from sea swells

the surface becomes rough, as the factors contributing to the roughness are now wide and varied ranging from distant wind storms to local disturbances, gravitational effects, man made interventions including ships, etc. As well, the boundary conditions imposed on these disturbances are complex and dynamic, ranging from natural obstacles such as shorelines and reefs to man made obstacles including oil rigs, bridges, and even large ships such as oil tankers, etc.

Based on simulation trials, the spatial diversity technique appears to perform relatively well against the effects of rough surface multipath. As with the smooth surface case, rough sea multipath is essentially a height dependent phenomenon, and as such, produces a varied response for different heights of the receive antenna, which is exploited by the jog detector. Although the spatial diversity technique offers better performance than the single antenna approach, there are some potential limitations which must be addressed. The next subsection discusses two in particular.

Potential Limitations

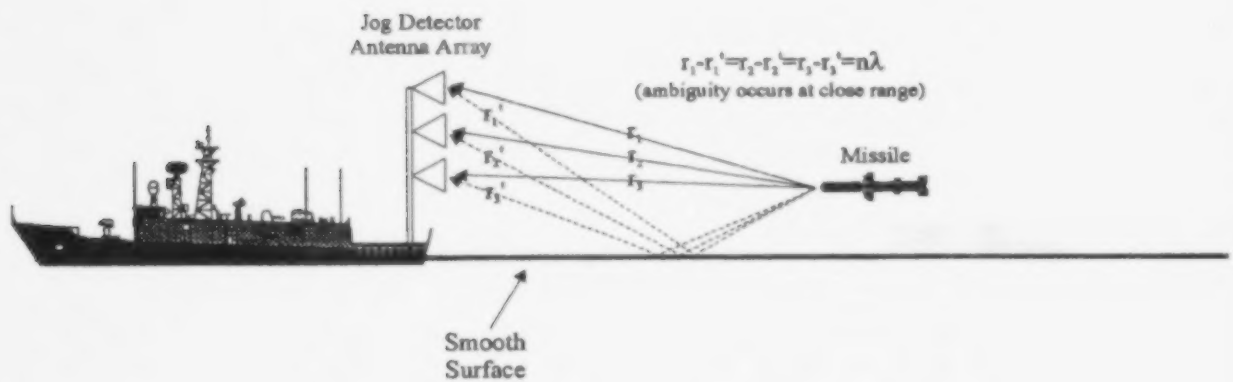
It is possible for some false jog readings to be measured with the spatial diversity technique due to the ambiguous path length readings from the different crests of the sea swells. This is illustrated in figure 3-44. In this example, three swell peaks contribute significant reflections towards the jog detector antenna array. The direct paths and corresponding indirect paths subtract to yield the same number of wavelengths ($r_1 - r_1' = r_2 - r_2' = r_3 - r_3' = n\lambda$). Consequently, when the direct and indirect signals vectorially combine at each antenna, the same fade occurs yielding false jog readings. The extent of this problem is yet unknown; experiments at sea, under realistic environmental conditions, is necessary to capture and analyze the effects of sea swell disturbances on the spatial diversity technique.

The second limitation is it measures fades on the basis of the seeker's antenna radiation pattern, making it dependent on the shape and size of the antenna pattern, as discussed above for the single antenna method. Therefore, to adequately measure jog fades, requires the antenna deflections to be significant relative to the antenna's HPBW.

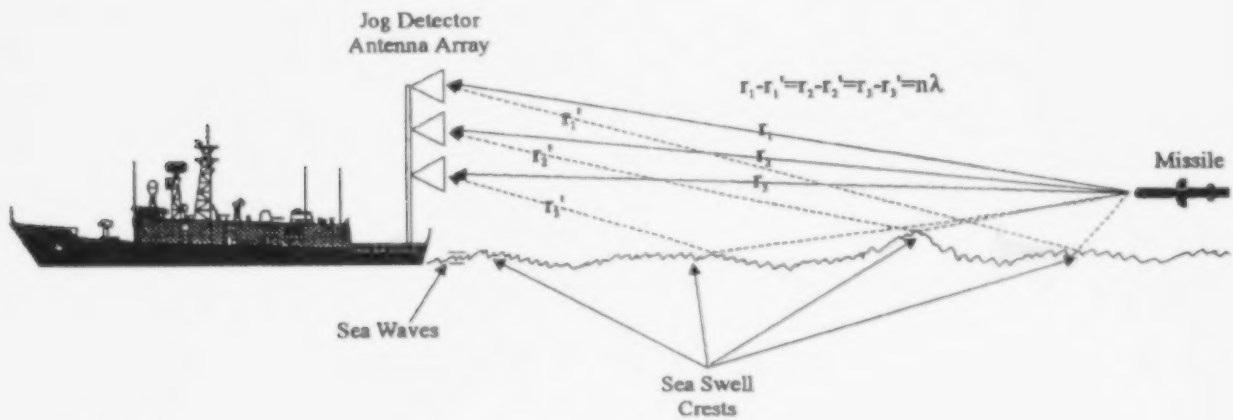
3.3.4 Summary

This section summarizes and compares the three principal jog detection techniques discussed above. Refer to table 3-5 for a brief description of each technique, along with their associated advantages and disadvantages. Individually, the techniques may not be completely effective or reliable, however, when combined in an integrated manner, they can offer a more robust jog detection capability to support ECM effectiveness assessment.

Of the three techniques analyzed, the measurement of antenna reflections appears to hold the most promise. Firstly, this technique can measure slight antenna movements, offering the best performance when there is either a mismatch in polarization or frequency between the jog



a) Path length ambiguities from smooth surface reflections



b) Path length ambiguities from rough surface reflections

Figure 3-44 Path length ambiguities from smooth and rough surfaces

detector's radar antenna and seeker antenna. Secondly, the jog detector radar has complete control over its transmit parameters, hence, it can resort to diversity (e.g. PRI stagger, RF agility, etc.) to overcome environmental effects such as multipath and clutter. Thirdly, this technique can measure jogs of passively guided systems, such as an ARM. One main drawback of this technique is that it has to transmit, which may serve to beacon the missile or help the enemy establish targeting information more precisely. Secondly, sophisticated hardware is required for a coherent capability. Finally, this technique is ineffective against phased array antennas which are physically slanted off target boresight while the mainbeam is electrically steered towards the ship.

Measuring amplitude changes is perhaps the simplest way to achieve jog detection, however, the technique works only with active systems. A single antenna could be used, or a vertical array of antennas to offset the destructive effects of multipath. In both cases, the fade measurement is dependent on the size and shape of the antenna power radiation pattern, hence, the antenna has to deflect on the order of a half power beamwidth or so for the fade to be appreciable enough to be measured. An advantage of amplitude measurement is that the technique is passive. A vertical array offers better performance over the single antenna approach against the ambiguous effects of multipath. Also, with a vertical array, the measurements are not degraded by ship motion (in fact, the movement of the ship may actually facilitate multipath discrimination).

Finally, measuring the variation in X-pol to Co-pol signal levels is another possible method for achieving jog detection. This technique offers the advantage of measuring slight jogs while being completely passive. The primary disadvantage with this approach is that it requires a dual polarized antenna with sensitive receivers to extract the X-pol information. Also, this technique is not effective against passive systems.

References

- [1] Balanis, C. A; Antenna Theory: Analysis and Design, Harper and Row, Publishers; Philadelphia, 1982; pp. 63 - 65
- [2] Doucet, K.R., Application of spatial diversity for jog detection in the presence of multipath effects, DREO report no. 1066.

Table 3-5 Summary of jog detection techniques

Jog Detection Technique	Description	Advantages	Disadvantages
Amplitude Variations • Single Antenna	• Measures power fades of seeker energy associated with jogs using a single antenna.	• Simple design • Operates passively	• Susceptible to multipath fades • Dependent upon seeker antenna shape and size (large deflections required for detection) • Not effective against passive systems • Ship motion can cause performance degradation
Amplitude Variations • Multiple Antennas	• Measures power fades of seeker energy associated with jogs using vertically stacked antennas.	• Discriminates against most multipath effects • Not degraded by ship motion • Operates passively	• More complicated design than single antenna • Dependent upon seeker antenna shape and size (large deflections required for detection) • Not effective against passive systems
X-pol/Co-pol change	• Measures variations in X-pol to Co-pol of seeker energy during jogs	• Sensitive to small angle deflections (for early jog indication) • Possible discriminator against multipath effects • Operates passively	• Dual polarization antenna and specialized equipment required • Not effective against passive systems
Antenna Reflections	• Measures reflections off the seeker antenna	• Can measure very slight seeker antenna movements for immediate jog detection • System has complete control over transmit parameters to minimize effects of propagation anomalies • Operates against passive systems.	• Radiation is required which may beacon the missile or help enemy in targeting • Sophisticated hardware required • Cannot use during EMCON • Ineffective against seeker antennas slanted off target boresight.

3.4 Chaff Reflections

3.4.1 Introduction

The purpose of this section of the report is to provide visibility into the use of chaff reflection measurements in support of ECM effectiveness assessment. More specifically, the detection of RF energy emanating from the direction of a chaff cloud may be indicative of a situation where a threat seeker has locked onto, and is obviously therefore illuminating, the chaff cloud. The observation of such reflected RF signals may be construed as evidence that the threat has been successfully decoyed by the chaff decoy.

The following topics will be discussed:

- Definition of a generic tactical environment in order to provide a context for this effectiveness assessment technique;
- General description of an approach to effectiveness assessment based on modelling bi-static radar scattering to predict the quantity of seeker energy (power) that will be measured (by an ownship ESM system) in the form of reflections from a deployed chaff cloud. Discussion of varying levels of model sophistication and identification of the problem of uncertain information; and
- Provision of detailed information concerning the evaluation of bi-static radar cross-section - a necessary element in support of the modelling of seeker chaff reflections.

3.4.2 Definition of Scenario

In order to elaborate the functionality associated with this particular effectiveness assessment technique, it is helpful to specify a generic tactical scenario. This will provide a realistic contextual framework within which the details of this method for assessing ECM effectiveness can be worked out. The definition of the tactical scenario will provide an indication of the tactical intent associated with the deployment of chaff. The latter will address the expected threat response, as potentially observable to the ship, associated with the successful deployment of the chaff decoy.

As the material in this section will demonstrate, the effectiveness assessment technique under consideration requires a fairly comprehensive characterization of the combat environment in which the countermeasure is operating. In particular, measured or inferred threat characteristics (e.g. ERP, antenna gain, etc.) as well as engagement geometry (e.g. position of threat, ship, and chaff cloud) are central to using chaff reflections as a technique for performing effectiveness assessment.

The tactical scenario to be specified will consist of a single missile threat that has been launched

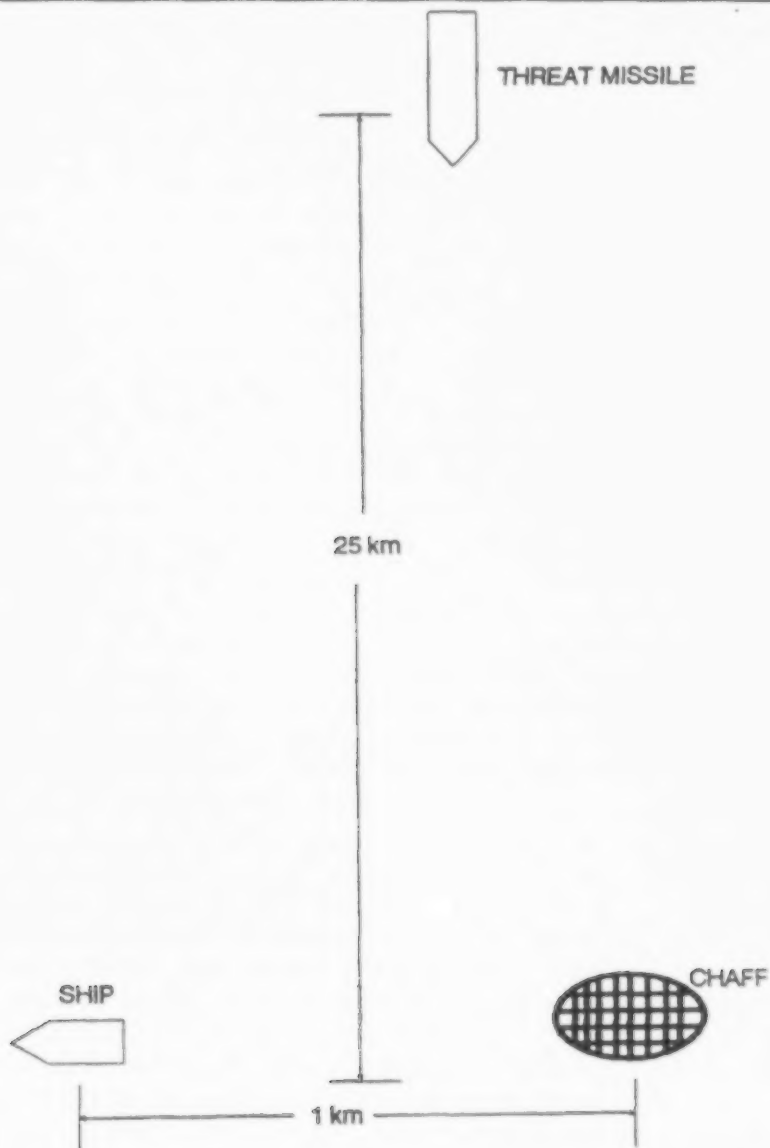


Figure 3-45 Engagement Scenario - Confusion Chaff

with the objective of destroying a single ship (Figure 3-45). The threat is assumed to be a surface launched supersonic medium range sea skimming missile equipped with an active radar seeker that employs monopulse angle tracking. The threat flies to a range of 25 km from the ship and then activates its seeker and begins searching for targets.

In order to defend itself, the ship deploys a single chaff cloud in the confusion regime - the chaff cloud is intended to serve as an alternate target for the threat seeker when it is executing its search function. If the tactic is successful, the threat seeker will detect the chaff cloud, lock-on to it and fly towards the cloud and (hopefully) away from the immediate vicinity of the ship. Once the threat is in track mode against the chaff cloud, RF reflections from the chaff cloud should be detectable by a shipborne ESM system. The detection of such reflections, and the determination that they indicate that the threat seeker has locked onto the chaff cloud, is the essence of the ECM effectiveness assessment technique under consideration.

Notwithstanding the provision of a specific tactical scenario as enumerated above, chaff reflection measurements can contribute to ECM effectiveness assessment in other contexts where the use of chaff is involved. The particular scenario addressed above is provided for illustrative purposes only and it should not be inferred that substantively different techniques are involved for other scenarios.

For example, the successful use of seduction chaff will result in a different chaff reflection profile than would be observed for the case of distraction chaff. Because seduction chaff is initially deployed very close to the ship, chaff reflections measured early in the engagement may not be as significant as those measured later in the engagement when some measure of separation between ship and chaff has been achieved. After all, if the chaff cloud is near the ship, seeker reflections from the chaff cloud may be present even if the seeker is effectively locked onto the ship. If the deployment is successful, the level of measured chaff reflections should remain high as the chaff separates from the ship, indicating that the seeker is tracking the chaff cloud.

3.4.3 General Discussion of Effectiveness Assessment Technique

Chaff reflection measurements may provide support to the hypothesis that the threat seeker is illuminating / tracking the chaff cloud. As such, these measurements contribute to a determination of whether the chaff cloud has fulfilled its role as a decoy. In particular, reflections from a chaff cloud can be integrated with other information in order to provide evidence that the seeker is preferentially illuminating the chaff cloud as compared with the ship. The basic approach is to model the effect that a successful chaff deployment will have on the measured characteristics associated with chaff reflections. Of primary interest will be to model, or predict, the strength of the reflection signal that would be consistent with a successful deployment of chaff. The signal strength derived from this prediction can then be compared with chaff reflection signal strengths as measured by an on-board ESM receiver. However, measurement of other attributes of the reflected signal (i.e. frequency, PRF, etc.) will also contribute to effectiveness assessment. Such attributes will be used to establish that the signal

received from the chaff is associated with the threat's seeker.

The signal strength (i.e. signal amplitude) has effectiveness assessment value specifically because of the directional characteristics of the threat seeker antenna. More specifically, as the angle between the seeker's boresight and the line [seeker-chaff] gets smaller, more seeker energy will be illuminating the chaff cloud. Therefore, there will be more scattering from the chaff cloud. Consequently if the seeker is indeed tracking the chaff cloud, the magnitude of seeker reflections from the chaff (as measured by the ship's ESM system) should be a maximum (Figure 3-46). Other reflection signal characteristics (such as frequency, PRF, etc.) should be relatively insensitive to whether the seeker is pointing at the chaff cloud or at the ship or elsewhere.

It is important to underscore the fact that the use of chaff reflections for the purposes of effectiveness assessment has a strong geometry dependence. There are some geometries for which the observation of chaff reflections has little, if any, effectiveness assessment value. Consider the case where both ship and chaff lie directly along the seeker boresight with the chaff cloud therefore receiving full seeker illumination. This situation may produce significant reflections, even though the seeker may be locked onto the ship. Chaff reflection measurements only have effectiveness assessment value when there is some meaningful angular separation between the line of sight from the seeker to the ship and the line of sight from the seeker to the chaff. In such cases, the measurement of reflections indicates that significant seeker power is being directed in a direction other than that of the ship.

For a specific engagement geometry, the shape of the seeker beam pattern is also a factor in determining the conditions under which the proposed method can be used. If the seeker's half-power beamwidth (HPBW) is relatively large, then it can reasonably be expected that relatively little change in received energy would be measured by an observer (ESM system) as he moves away from boresight. Stated in the vernacular, the beam pattern is relatively "flat" in the vicinity of the boresight. That this might impose constraints on the application of the proposed technique will be illustrated by example.

Consider the engagement geometry represented in Figure 3-45. It can be easily shown that the angular difference between threat seeker line of sight to the chaff and the seeker line of sight to the ship is approximately 2° . Consider also that the threat seeker HPBW is approximately 4° . In such a circumstance the chaff will receive substantial radar illumination even if the seeker is pointing at the ship. It may, therefore, be difficult to determine which object the threat is tracking under these conditions. In order to resolve this ambiguity, it may be desirable to maintain a time-history of chaff reflection levels. Chaff reflection signal attributes other than amplitude do have some value in determining effectiveness. In particular, measured chaff reflection signal attributes can be compared to the corresponding characteristics of the seeker signal. This mechanism ensures that the source of the reflections emanating from the chaff is indeed the seeker that is under prosecution and not some other radar (for example, ownship fire control radar). It should be stated that the level of ownship knowledge of the threat seeker characteristics may vary significantly from situation to situation. For example the quality of

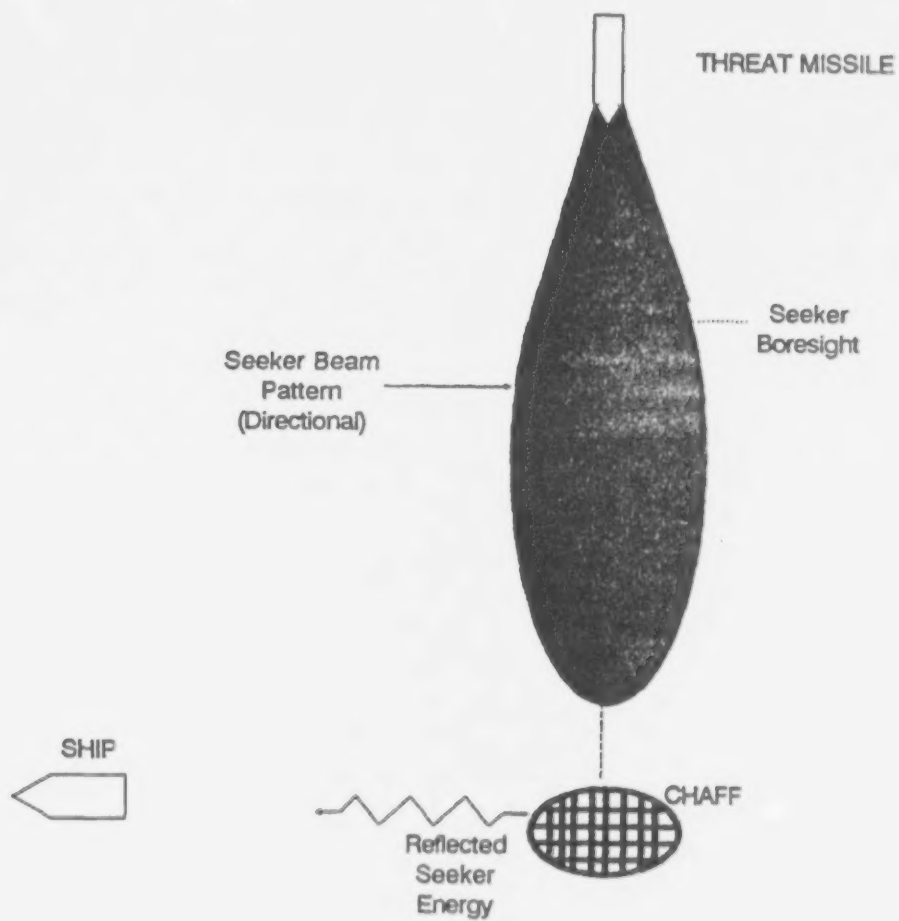


Figure: 3-46 Seeker Reflections From Chaff

seeker information available when deploying chaff in a confusion regime is likely to exceed that available under the seduction regime. Seduction chaff is deployed to counter a seeker that is already tracking the ship; hence a detailed emitter profile will likely have been developed by an ESM system. Conversely, confusion chaff may be deployed before the seeker has even entered search mode; a detailed signal profile describing the seeker may not yet be available. The model to be used in order to predict the chaff reflection signal strength associated with successful chaff deployment is based upon the application of the bi-static radar range equation. This equation is descriptive of situations where a source of RF energy illuminates a scatterer and produces reflections that impinge upon a radar receiver that is not co-located with the transmitter. Indeed, in the situation under consideration, the transmitter is the threat seeker whereas the radar receiver is effectively the shipborne ESM system. The scatterer is, quite obviously, the chaff cloud.

One form of the bi-static radar equation is given as follows:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma_b}{(4\pi)^3 D_t^2 D_r^2 L_p(t) L_p(r) L_s} \quad (46)$$

where

- P_r = received signal power, watts
- P_t = transmitter power, watts
- G_t = transmitting-antenna gain in direction of target
- G_r = receiving-antenna gain in direction of target
- σ_b = bi-static cross section, m^2 (discussed later)
- D_t = transmitter-to-target distance, m
- D_r = receiver-to-target distance, m
- $L_p(t)$ = propagation loss over transmitter-to-target path
- $L_p(r)$ = propagation loss over receiver-to-target path
- L_s = system loss
- λ = wavelength, m

The effect of the directional characteristics of the threat's seeker antenna are manifested by the parameter G_t . G_t is in reality a function of the angle Θ between the seeker boresight and the line of sight from the seeker to the chaff cloud. If the seeker is pointing directly at the chaff cloud, Θ will be effectively 0 and the value of G_t will be maximized. Note that it is frequently useful to approximate $G_t(\Theta)$ using a Bessel function:

It is clear that, in order to use equation (47) to generate a prediction of the strength of chaff reflections, a number of parameters that characterize the combat environment need to be known. Some of these parameters are specific threat attributes such as seeker transmitter power, seeker antenna gain, and the wavelength of the transmitted signals. The first two are not directly measurable by ownship and need to be inferred from other measurements / evaluations. For

$$G_r(\theta) = G_{\max} \left[2 \cos \theta \frac{J_1\left(\frac{2\pi}{\lambda} a \sin \theta\right)}{\left(\frac{2\pi}{\lambda} a \sin \theta\right)} \right]^2 \quad (47)$$

where

- $G_{\max}$ = Maximum gain
- J_1 = Bessel function of the first kind, order one
- a = Antenna radius (circular antenna)
- θ = Angle between boresight and LOS to chaff
- λ = Transmitted signal wavelength

example, once measurements of frequency, PRF, etc. have been made, a hypothesis concerning target identity can be generated. In turn, the proposed target identity can be used to infer the seeker's effective radiated power as well as its antenna gain. Conversely, the wavelength of the transmitted signal is a quantity that is measurable by the ownship ESM system.

Other parameters associated with the bi-static radar range equation are characteristics of the geometry and environmental conditions associated with the transmitter - scatterer - receiver system. Such parameters include the transmitter - to target distance, the receiver-to-target distance, and the propagation loss parameters.

A knowledge of the characteristics of the ESM system that is being used to perform chaff reflection measurements is needed in order to predict measured signal strength. In particular, the receiving antenna gain and the system loss parameters are characteristics of the shipborne ESM system.

Finally, the bi-static radar cross section is a parameter whose estimation or prediction requires the application of relatively complex methods. The derivation of bi-static RCS, to be addressed in detail in Section 3.4.4 of this report, is based on such widely diverse parameters as threat seeker polarization, ESM receiver polarization, scattering geometry, and the number of chaff dipole strips.

Although it is frequently a concern when processing radar signals in a naval context, the multipath effect is not a significant factor in this particular context. In general, multipath signals can combine with line - of - sight signals to produce a fading effect as signals interact constructively and destructively. However, the relatively short range of the chaff cloud from the ship combined with chaff cloud heights generally in excess of ≈ 100 m result in a geometry where multipath effects are minimal. Furthermore, the fact that the chaff cloud is spatially

extended target reduces the effect of multipath contributions.

Once all necessary parameters have been evaluated / estimated, the bi-static radar equation can be solved and measurements of received power (from the direction of the chaff cloud) can be compared with this predicted amount.

The model that the NEWCP employs to predict chaff returns can be arbitrarily complex. In the most general case, the problem involves an attempt to characterize a complex phenomena (chaff scattering) in a specific tactical context. Attempts to model this problem can be as simple as computing the expected received reflection power associated with the successful deployment of a static (non-blooming, non-decaying) chaff cloud. Such an approach would involve the computation of expected reflection levels assuming that the threat has locked onto the chaff cloud. Note that there is no attempt to model when this lock-on condition might be expected. Alternately, the model can, in principle be more dynamic in nature.

A dynamic model would explicitly account for the temporal dimension of the problem domain. For instance, it is possible to predict, to some degree of accuracy, the expected time profile of events associated with the chaff deployment. In other words, the predicted chaff signal reflection level will depend on the specific timeline associated with the deployment. For example, it may be reasonable to assume that (for the case of confusion chaff) threat lock-on to chaff will occur at some point after 10 seconds have elapsed since chaff canister explosion (assuming that chaff bloom time is about 10 seconds). If the observed signal strength time profile is consistent with this, confidence that chaff has performed its function will be increased.

By comparison, consider the case where observed chaff reflection levels are consistent with those predicted by the bi-static radar equation, but where there is no time correlation between prediction and observation. This might occur if the predicted signal level associated with a successful confusion chaff deployment is observed 1 second after chaff canister explosion. Despite the agreement between predicted and observed signal levels, the lack of temporal correlation might indicate that the observed signal does not necessarily indicate that the particular threat under prosecution has been decoyed.

There are additional ways in which the model used to predict chaff reflections could be made more complex. The chaff cloud RCS is not in fact static. Instead it varies in a complex way with time. The following equation represents one way of characterizing the variation of chaff RCS (σ) with time:

$$\sigma(t) = \sigma_{max} * [(t/T_{bloom})^K] \exp[K * (1 - t/T_{bloom})]$$

$$\text{where } K = 1 / ((T_{decay}/T_{bloom}) - \ln(1 + T_{decay}/T_{bloom}))$$

(48)

t = Time

T_{bloom} = 10 seconds (representative value)

$$T_{decay} = 180 \text{ seconds (representative value)}$$

Figure 3-47 illustrates the time dependency of chaff radar cross-section.

As the preceding material has implied, the proposed technique for effectiveness assessment is based on modelling a complex problem domain characterized by a number of variables. The degree of certainty associated with the measurement / estimation of most of these parameters is highly variable. Accordingly, the confidence that can be attributed to effectiveness assessment evidence that is based on chaff reflection measurements will vary in a commensurate manner. There is therefore a requirement for a scheme that will serve to quantify the uncertainty associated with effectiveness assessments based on chaff reflection measurements. A discussion of methods for handling the uncertainty associated with effectiveness assessment problems is provided in Section 7 of this report.

3.4.4 Determination of Bi-static Radar Cross Section

The purpose of this section is to provide explicit equations for the chaff bi-static cross section presented to a receiving antenna having arbitrary (elliptical) polarization and arbitrary location. Furthermore, the line of sight from the receiving antenna to the chaff cloud is considered as arbitrary. Finally, the transmitter is considered to be arbitrarily located and have arbitrary polarization.

The material presented in this subsection is directly based upon the findings of a paper entitled "Bi-Static Radar Cross Sections of Chaff", written Peyton Z. Peebles, Jr. (University of Florida, Electronic Communications Laboratory).

The overall geometry applicable to bi-static scattering is shown in Figure 3-48. A transmit antenna located at point T radiates an arbitrarily polarized electromagnetic wave toward a cloud of randomly positioned and randomly oriented dipoles represented by point D. The transmit direction is defined by spherical coordinate angles Θ_1 and Φ_1 , defined in the common x,y,z coordinate frame. The dipole cloud is assumed to be far enough from the transmitter in order to ensure that the wave incident upon the cloud is planar. Cloud extent is assumed to be small enough in relation to average distance, denoted by r_1 , so that the strength of the incident field is approximately the same for all dipoles.

Scattering between dipoles is assumed negligible, and dipoles are presumed sufficiently dispersed that mutual coupling is of no concern. It has been shown that dipoles spaced at least two wavelengths apart in any direction produce almost no mutual coupling. Dipoles are assumed to zero-resistance wires with a length that produces resonance at the transmitter frequency. In many practical cases, dipole size and material are such that dipole losses are negligible.

As illustrated in Figure 3-47, a typical dipole scatters some energy in the direction of a receiver, at point R, whose angular position is defined by spherical angles Θ_2 and Φ_2 . The receiving

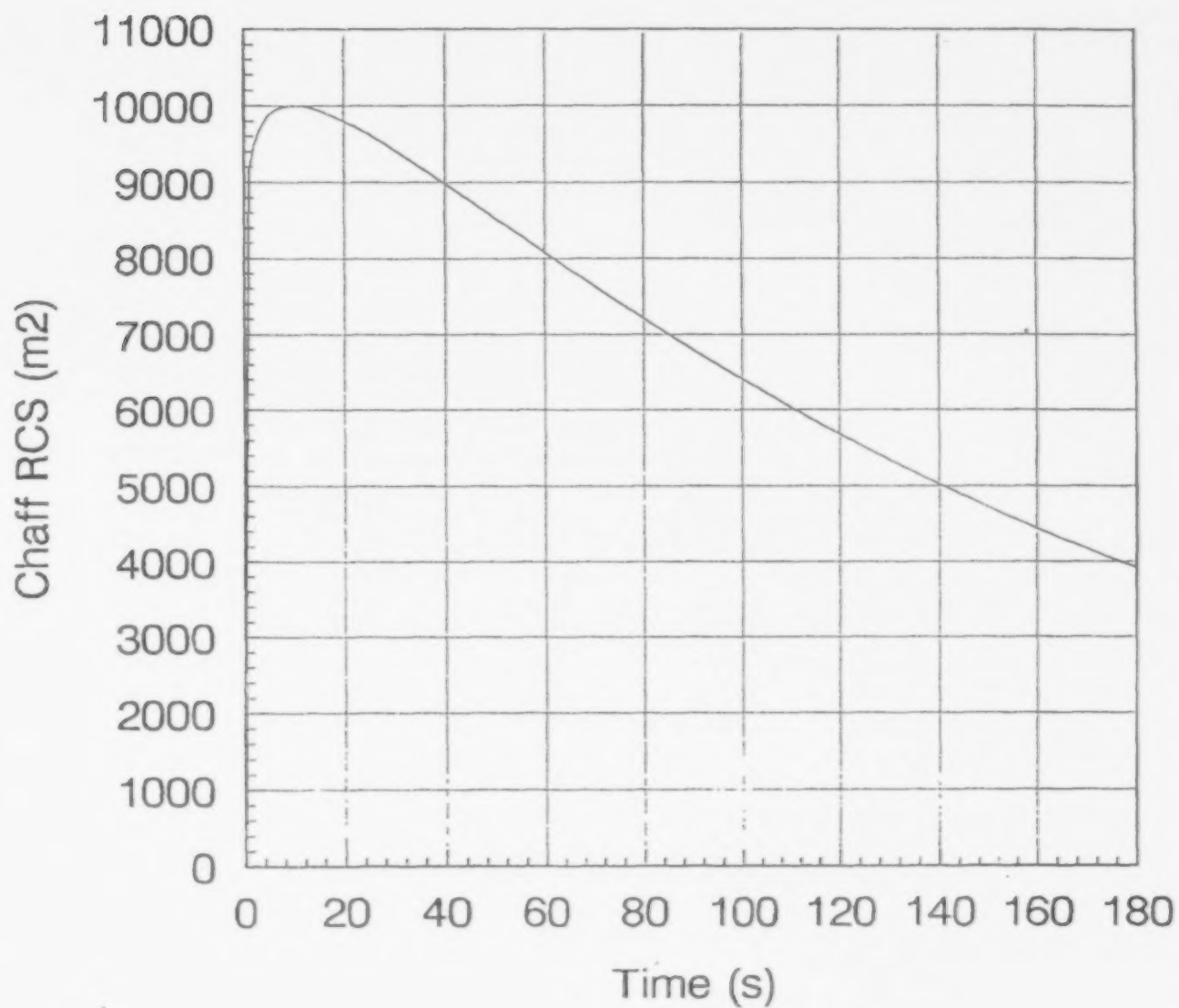


Figure 3-47 Chaff Radar Cross Section Variation with Time

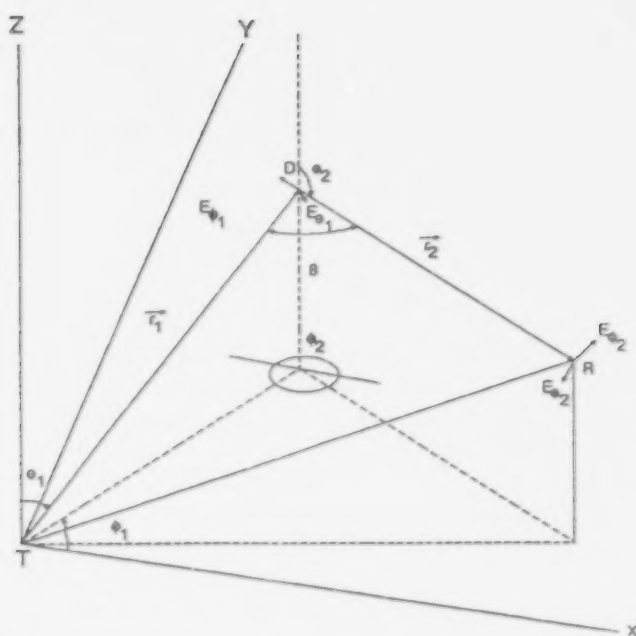


Figure 3-48 Bi-Static Scattering Geometry

antenna is assumed to be far enough away from all the dipoles in the cloud being viewed by the receiver antenna. Accordingly, all dipole - receiver path distances are approximately equal to the average distance, denoted by r_2 . The receiver is arbitrarily located, and the angle between its line of sight (RD) and the radar's line of sight (TD) is called the bi-static scattering angle, denoted by β .

Both transmit and receive antennas are presumed to be arbitrary; that is, they are elliptically polarized. By employing the usual complex envelope representation of fields, one can define the transmitted (or received) field polarization by a complex quantity Q (Q_T for transmitter, Q_R for receiver) that equals the complex field in the Φ direction (Φ_1 for transmitter, Φ_2 for receiver) divided by the complex field in the Θ direction (Θ_1 for transmitter, Θ_2 for receiver). The electric field of the wave incident on the dipole cloud is denoted by E_1 ; it has components in directions Θ_1 and Φ_1 and its polarization is determined by Q_T . The electric field vector of the wave arriving at the receiver, denoted by E_2 , can be decomposed into the sum of (1) an electric field vector, denoted by E_{R1} , of an elliptically polarized wave having the receive antenna's polarization, defined by Q_R , and (2) a second wave's electric field vector, denoted by E_{R2} , having the orthogonal polarization also defined by Q_R .

With the above definitions, we define bi-static radar cross section, denoted by σ , based on the power arriving at the receiver in the receiver's preferred polarization according to:

$$\sigma = \lim_{r_2 \rightarrow \infty} \frac{|\vec{E}_{R1}|^2}{|\vec{E}_1|^2} = 4\pi r_2^2 |\vec{E}_{R1}|^2 / |\vec{E}_1|^2 \quad (49)$$

A cross section, denoted by σ_x , can also be defined for power arriving at the receiver in the orthogonal polarization by:

$$\sigma_x = \lim_{r_2 \rightarrow \infty} \frac{|\vec{E}_{R2}|^2}{|\vec{E}_1|^2} = 4\pi r_2^2 |\vec{E}_{R2}|^2 / |\vec{E}_1|^2 \quad (50)$$

The approximations in equations 49 and 50 are true because it is assumed that r_2 is relatively large. These cross-sections depend upon the exact dipole positions and orientations. A reasonable approach to reducing the complexity associated with evaluating these equations for each chaff dipole is to take advantage of the random nature of dipole positions and orientations by treating these quantities as random variables and averaging to get average cross sections, denoted by σ and σ_x . By using $E[\cdot]$ to denote the statistical average we have:

$$\bar{\sigma} = 4\pi r_2^2 E [|\vec{E}_{R_1}|^2] / |\vec{E}_1|^2 \quad (51)$$

$$\bar{\sigma}_x = 4\pi r_2^2 E [|\vec{E}_{R_2}|^2] / |\vec{E}_1|^2 \quad (52)$$

The values of σ and σ_x are functions of the geometry of the transmitter - chaff cloud - receiver system as well as of the transmit and receive antenna polarizations and the number and length of the chaff strips. It can be shown that the values of σ and σ_x are given as follows:

$$\begin{aligned} \bar{\sigma} = & \frac{N}{(1 + |Q_T|^2)(1 + |Q_R|^2)} \{ (\bar{\sigma}_{\perp \perp \perp} |W_1|^2 + \bar{\sigma}_{\perp \parallel \parallel} |W_2|^2) |x_1|^2 \\ & + (\bar{\sigma}_{\perp \parallel \perp} |W_1|^2 + \bar{\sigma}_{\parallel \parallel \parallel} |W_2|^2) |x_2|^2 \\ & + 4\bar{\sigma}_A \operatorname{Re}(W_1 W_2^*) \operatorname{Re}(x_1 x_2^*) \} \end{aligned} \quad (53)$$

$$\begin{aligned} \bar{\sigma}_x = & \frac{N}{(1 + |Q_T|^2)(1 + |Q_R|^2)} \{ (\bar{\sigma}_{\perp \perp \perp} |W_2|^2 + \bar{\sigma}_{\perp \parallel \parallel} |W_1|^2) |x_1|^2 \\ & + (\bar{\sigma}_{\perp \parallel \perp} |W_2|^2 + \bar{\sigma}_{\parallel \parallel \parallel} |W_1|^2) |x_2|^2 \\ & - 4\bar{\sigma}_A \operatorname{Re}(W_1 W_2^*) \operatorname{Re}(x_1 x_2^*) \} \end{aligned} \quad (54)$$

where $\operatorname{Re}(\cdot)$ represents the real part of the complex quantity in parentheses, * denotes complex conjugation, and

$$x_1 = T_1 - T_2 Q_T \quad (55)$$

$$x_2 = T_2 + T_1 Q_T \quad (56)$$

$$T_1 = \sin \theta_2 \sin(\phi_1 - \phi_2) / \sin \beta \quad (57)$$

$$T_2 = [\sin \theta_1 \cos \theta_2 - \cos \theta_1 \sin \theta_2 \cos(\phi_1 - \phi_2)] / \sin \beta \quad (58)$$

$$W_1 = R_1 - R_2 Q_R \quad (59)$$

$$W_2 = R_2 + R_1 Q_R \quad (60)$$

$$R_1 = \sin \theta_1 \sin(\phi_1 - \phi_2) / \sin \beta \quad (61)$$

$$R_2 = -[\sin \theta_2 \cos \theta_1 - \cos \theta_2 \sin \theta_1 \cos(\phi_1 - \phi_2)] / \sin \beta \quad (62)$$

N is the number of dipoles being illuminated by the transmitter that exist in the volume viewed by the receiver's antenna, and $\sigma_{\perp \text{ to } \perp}$, $\sigma_{\perp \text{ to } \parallel}$, $\sigma_{\parallel \text{ to } \parallel}$, and σ_{Δ} are four functions that depend only on β (for a given dipole length).

The variables $\sigma_{\perp \text{ to } \perp}$, $\sigma_{\perp \text{ to } \parallel}$, $\sigma_{\parallel \text{ to } \parallel}$, and σ_{Δ} can be evaluated as follows:

$$\bar{\sigma}_{\perp \text{ to } \perp} = 4\pi r_2^2 |B|^2 E [A_0^2(\theta_d, \phi_d) \cos^4 \theta_d] c \quad (63)$$

$$\bar{\sigma}_{\perp \text{ to } \parallel} = 4\pi r_2^2 |B|^2 E \left[A_0^2(\theta_d, \phi_d) \cos^2 \theta_d \sin^2 \theta_d \sin^2 \left(\phi_d + \frac{\beta}{2} \right) \right] \quad (64)$$

$$\bar{\sigma}_\Delta = -4\pi r_2^2 |B|^2 E \left[A_0^2(\theta_d, \phi_d) \cos^2 \theta_d \sin^2 \theta_d \sin(\phi_d - \frac{\beta}{2}) \sin(\phi_d + \frac{\beta}{2}) \right] \quad (65)$$

$$\bar{\sigma}_{|\infty|} = -4\pi r_2^2 |B|^2 E \left[A_0^2(\theta_d, \phi_d) \sin^4 \theta_d \sin^2(\phi_d - \frac{\beta}{2}) \sin^2(\phi_d + \frac{\beta}{2}) \right] \quad (66)$$

where the spherical average is defined by:

$$E[.] = \frac{1}{4\pi} \int_{\phi_d=0}^{2\pi} \int_{\theta_d=0}^{\pi} [.] \sin \theta_d d\theta_d d\phi_d \quad (67)$$

In order to evaluate the above, the following additional information is required:

$$B \stackrel{\Delta}{=} \left[-j\pi/(2\lambda z_{rad} r_2) \right] \exp(-j2\pi r_2/\lambda) \quad (68)$$

$$A_0(\beta/2) \stackrel{\Delta}{=} A(\pi/2, \beta/2) A(\pi/2, -\beta/2) \quad (69)$$

$$A(\theta, \phi) \stackrel{\Delta}{=} \frac{(\lambda/\pi)}{\sin(\pi L/\lambda)} \cdot \frac{\cos[(\pi L/\lambda) \cos \psi] - \cos(\pi L/\lambda)}{\sin^2 \psi} \quad (70)$$

$$\cos \psi = \cos \theta \cos \theta_d + \sin \theta \sin \theta_d \cos(\phi - \phi_d) \quad (71)$$

z_{rad} = antenna impedance

L = dipole length (e.g. $k\lambda/2$, $k = 1, 2, 3, \dots$)

η = 120π (intrinsic impedance of free space $\approx 377 \Omega$)

4.0 Effectiveness Assessment for Search/Targeting Radars

This section describes the contextual or high level aspect of effectiveness assessment for search/targeting radar ECM techniques. The ECM techniques are essentially designed to counter the radar operator, who manually searches for the ship to establish its coordinates for pre-launch missile designation. Both elements of effectiveness assessment are difficult to achieve against this phase of the threat, i.e. assessing effectiveness and determining the expected response for comparison purposes. For example, it is difficult to determine the precise response of an operator in the loop controlling the radar, since reaction may vary for each person under different jamming circumstances. In this case, the NEWCP tries to exploit the more obvious possible outcomes, such as a non-missile launch due to the operator's inability to discriminate against jamming, etc. From a measurement point of view, it is difficult to assess ECM results against search radars which do not offer any clues as to when the ship has been targeted for missile attack. For example, the operator may use a track-while-scan (TWS) radar to keep track of the target, whereby the radar antenna continuously rotates or scans, before and after detection, giving no indication as to when the operator has actually established target contact. Finally, for the case where the enemy uses a third party platform to perform the targeting function, the radar parameters may not change when targeting information is communicated back to the launch platform, further complicating the assessment process for the NEWCP.

Another difficulty in assessing the effectiveness of ECM techniques against search radars pertains to the lengthy timeline associated with the measurement process. It can take up to minutes before ECM is declared a success. In a dynamic environment, where platforms are continually changing positions, radars are altering modes, and ECM is being deployed, it becomes extremely difficult to keep track of the threat's response to a particular ECM technique. The NEWCP must factor all of these into its TSA module, and assign the appropriate algorithms to deal with the uncertain information.

The difficulties described above underline the strong requirement for sensor data fusion, where data from a variety of sensors, as well as operator input, help to establish the tactical picture, and, more precisely, the threat's response to a particular jamming technique. For example, a ship's crewman may detect an incoming missile first, by making visual contact of the missile's plume. Based upon this information, the EWCP would cue, through the CCS, the appropriate sensors to track the missile for ECM deployment. Section 3 provided a review of the various low-level techniques available for supporting the high level assessment process. Refer to that section for details regarding sensor performance and parameters, including the effects of propagation anomalies.

Refer to figure 4-1 for a functional illustration of the different effectiveness assessment techniques that could support the various search/targeting radar ECM techniques. The low level effectiveness assessment techniques being addressed in this study are based on: i) missile trajectory deviations, ii) radar mode changes, iii) chaff reflections, and iv) antenna jogs. These techniques support the assessment of target detection denial and false target acquisition.

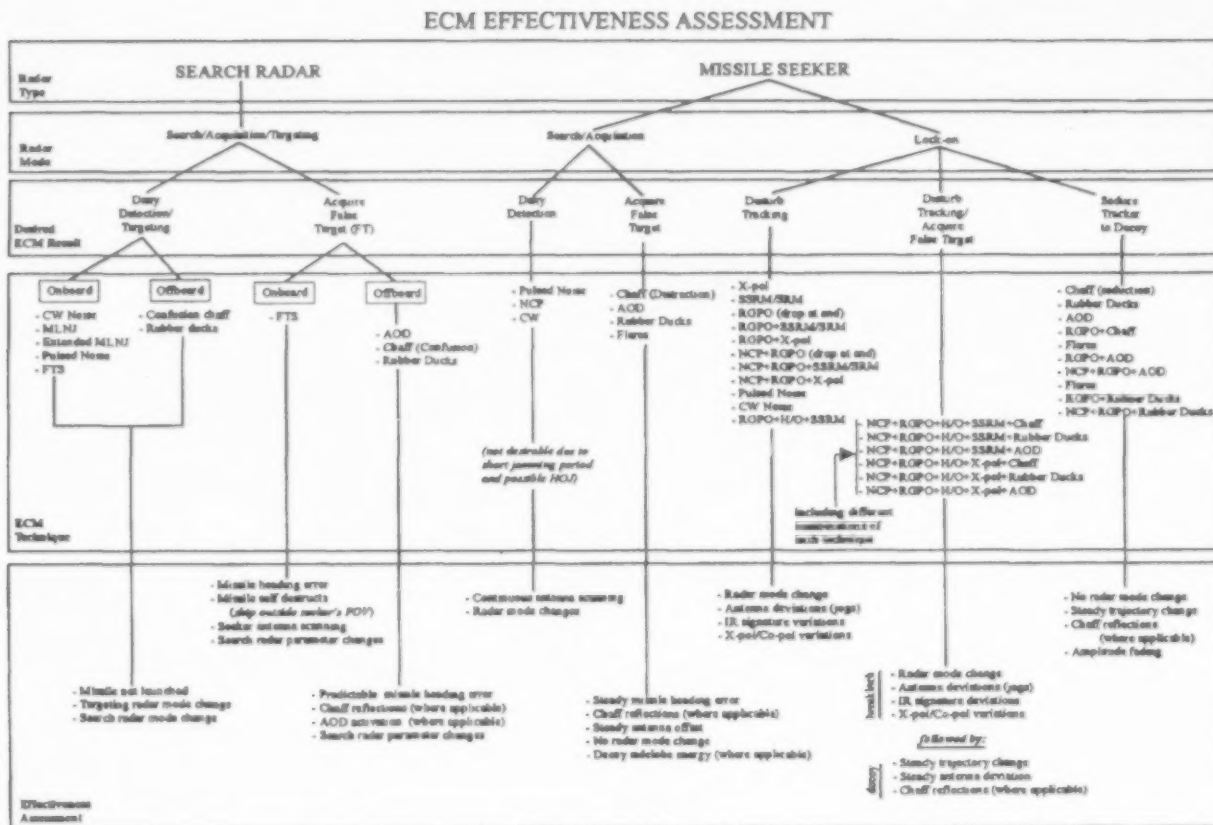


Figure 4-1 Effectiveness Assessment Matrix

4.1 Target Detection Denial

The goal of ECM, under this category, is to prevent the radar operator from detecting and establishing the coordinates of own ship for missile pre-launch designation. This can be achieved through the deployment of a number of ECM techniques including: CW noise, mainlobe noise jamming, extended mainlobe noise jamming, confusion chaff, rubber ducks, etc. Figure 4-2 provides a state diagram of events associated with effective ECM against a search/targeting radar.

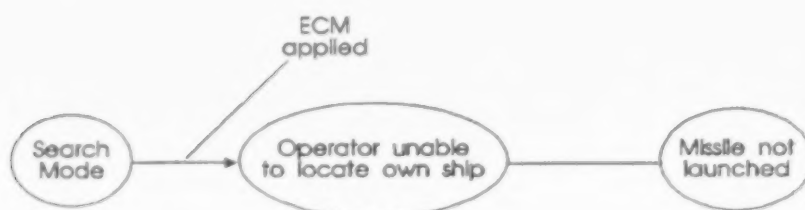


Figure 4-2 State diagram of search/targeting radar response to jamming

Events which can be observed or measured to assess ECM effectiveness include: non-missile launch, targeting radar mode change, and third party platform radar mode change.

4.1.1 Non-missile launch

The non-launching of a missile provides evidence ECM may have been effective in preventing the operator from establishing proper detection of own ship. A source of ambiguity with this assessment may be that the enemy had no intentions on firing in the first place, regardless of jamming. The EWCP will have to take this uncertainty into consideration, based on, among other things, input from the CCS.

Sensors which could be used to support this assessment include: visual contact, IRST, radar, ESM (for active seekers), and sonar.

Visual

When conditions permit it, one of the best means of determining if a missile has been launched is through visual contact. This may be achieved by a ship's crewmen, if the launch platform is within his/her optical horizon, or by an operator of a third party aircraft supporting own ship tactics. If it is not possible to observe the missile launch itself, then missiles that are detected approaching the ship provide strong evidence that ECM was unsuccessful.

The environment is the principal factor affecting visibility. The weather has to be relatively clear, as precipitation, such as rain and snow, and fog hamper performance significantly. For third party observation platforms which are at relatively high altitudes, there must not exist any low ceiling clouds which could impede visibility of the launch platform at long range. As

alluded to, the optical horizon also limits the range by which eye contact of the launch platform can be made, particularly from own ship. The optical horizon is approximately 25 km from ship to ship.

Radar

The radar in this case would be used to search for missiles approaching the ship. A detected missile would provide strong evidence to the EWCP that jamming was unsuccessful. Many parameters must be considered in addressing radar performance for missile detection - the most important being the monostatic RCS of the missile as viewed from the ship's radar (this is discussed in detail in section 3). Other parameters include radar transmit power, clutter, polarization loss factor (PLF), frequency difference between radar and missile seeker (for radar type seekers), scanning rate of the radar, radar antenna gain, etc. Clutter does not pose a problem for detecting high divers - the main difficulty with these systems, such as an ARM, is that they dive at extreme depression angles, falling outside the mainbeam of the radar to evade detection.

Of the sensors currently aboard the CPF, the SPS-49 would be the first radar to detect a missile, based on its performance specification. It has relatively high transmit power and sufficient receiver sensitivity to measure the RCS of typical missiles falling within the radar horizon, which is about 25-45 km for low altitude missiles, all the way out to <B1> km or so for high altitude threat systems. Figure 4-3 depicts the S/N ratio of clutter for a long range search radar, like the SPS-49, for wind velocities of 10, 20, 30, 40, and 50 kts. The results are based on the Engineer's Refractive Effects Prediction System (EREPS) software program developed by the Naval Ocean Systems Center (NOSC), Tropospheric Branch, Ocean and Atmospheric Sciences Division. The propagation factor defines the S/N figure for the target returns, taking into consideration the target radar cross section size, radar parameters, propagation losses, antenna patterns, clutter, refraction, receiver probability of detection and false alarms, system noise figure, etc. The horizontal dashed line is the detectability factor of the radar - the target is considered detected when the S/N value is above this line.

For this and the following set of graphs, the search radar height is 30 m, while the missile height is nominally 10 m above the surface. The head-on RCS of the missile is 1 m^2 . As shown in the figure, the search radar can detect the missile all the way out to the radar horizon, approximately 38 km, for wind speeds up to roughly 40 kts. The target is completely buried in clutter when the wind velocity exceeds 40 kts, assuming the radar has no moving target indicator (MTI) capability. A non-coherent MTI circuit would eliminate most of the clutter, but may introduce critical blind speeds, depending on the number of delay lines implemented.

The next figure, figure 4-4, shows the propagation coverage of the same radar as above in terms of height and range, with and without ducting. The top figure is with no surface ducts, while the lower figure is for a surface based duct height of 300 m, which is common in the Atlantic ocean. Recall that ducting is a condition that occurs when the refractive index of the atmosphere decreases below a critical gradient, causing the electromagnetic wave to bend downwards and

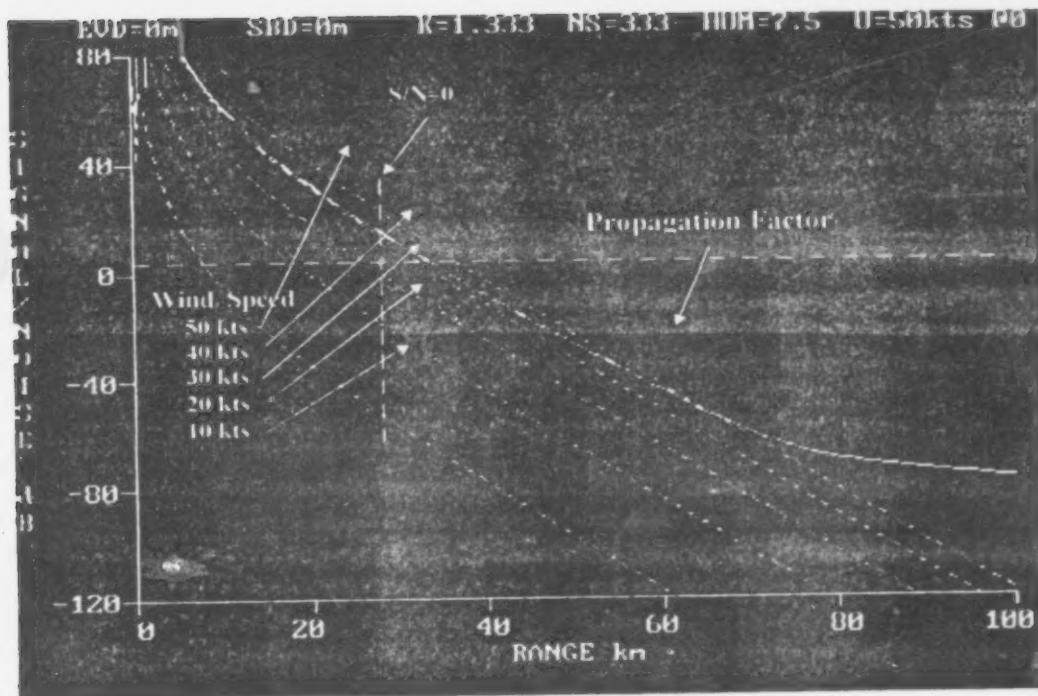


Figure 4-3

S/N response for long range search radar

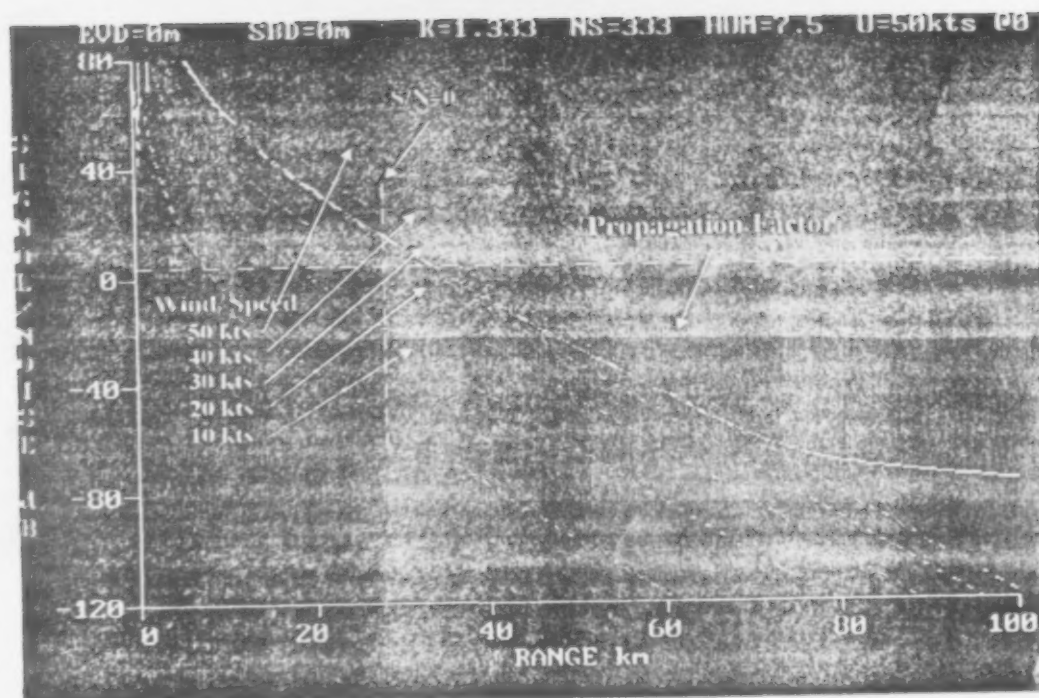
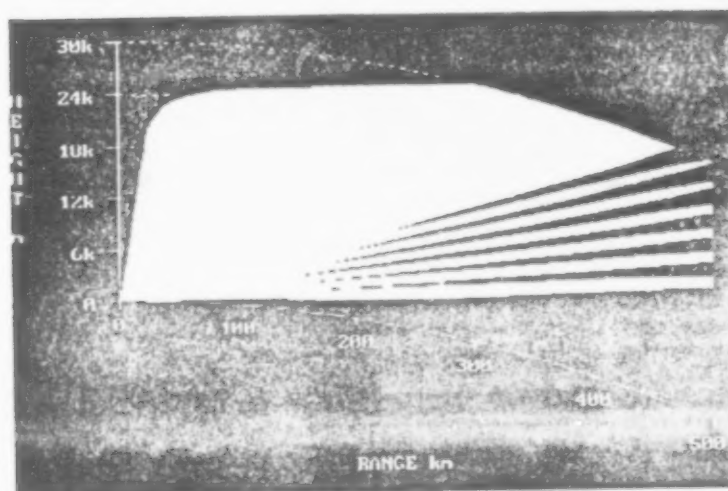
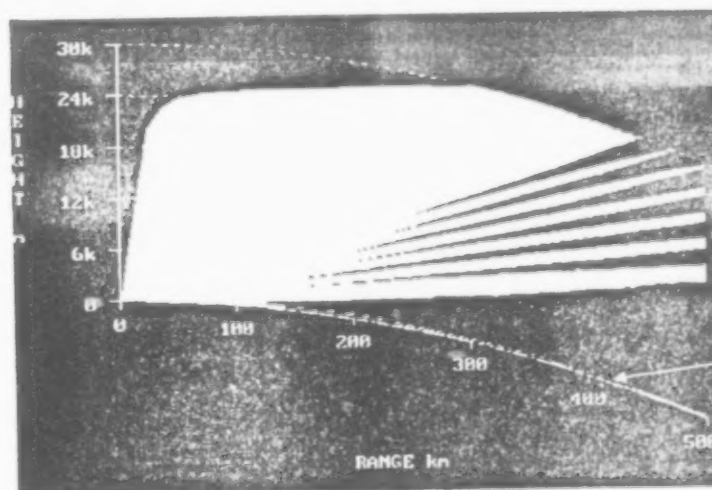


Figure 4-3

S/N response for long range search radar



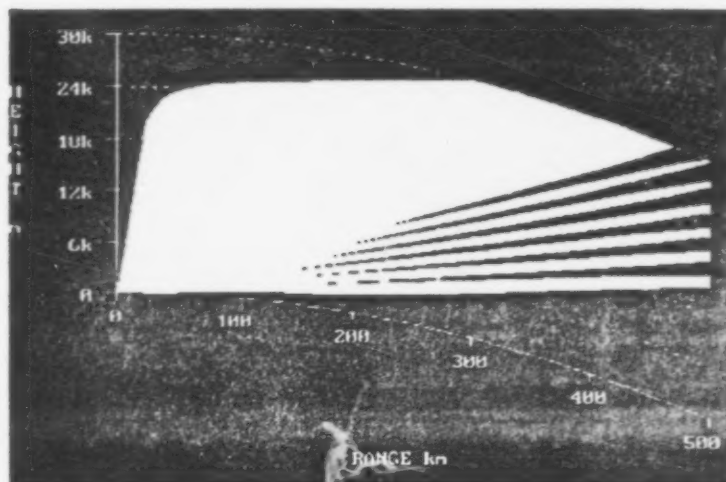
a) Propagation without surface based ducts



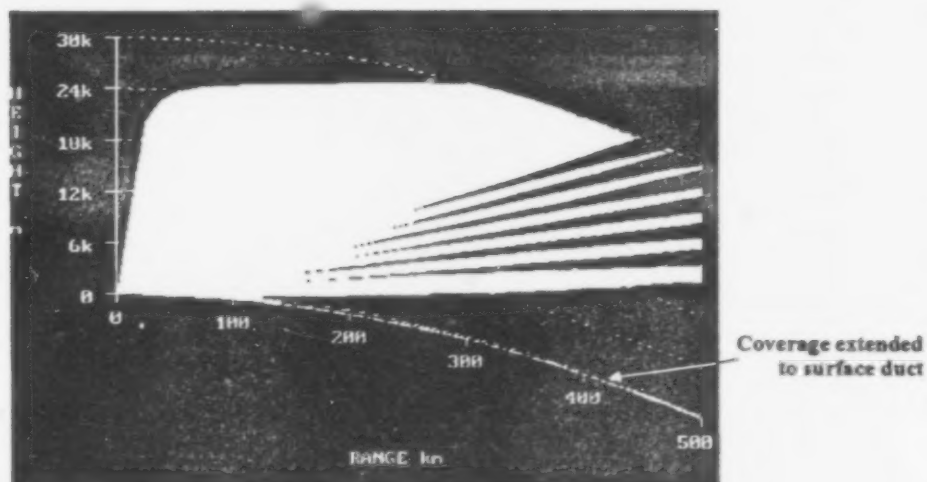
b) Propagation with 300 m surface based duct (elevated trapping layer).

Figure 4-4

Effects of ducting on long range search radar



a) Propagation without surface based ducts



b) Propagation with 300 m surface based duct (elevated trapping layer).

Figure 4-4

Effects of ducting on long range search radar

propagate in a waveguide type region just above the surface. Consequently, the radar signal travels further in the trapping layer than would be possible under normal propagation conditions.

As shown in the lower figure, the duct layer extends the coverage of the search radar well beyond the radar horizon for low altitude targets such as sea skimming missiles. The net effect of the duct is to essentially introduce a new antenna lobe near the surface and fatten the first lobe, while slightly reducing the remaining lobes. Figure 4-5 depicts the S/N response of the same radar and duct condition. It is seen that, in terms of detection, the radar performs the same for ranges up to the radar horizon, however, it can also detect the missile when it is between 100 and 300 km away. Interestingly, for a wind velocity of 50 kts, the search radar is unable to detect the missile at ranges below the radar horizon due to clutter (assuming no MTI capability), but is able to detect it at ranges between 100 and 300 km. This is because the surface clutter is not enhanced by the duct layer as is the case for the radar signal.

The next graph, figure 4-6 shows the effects of evaporation ducting on the long range search radar, which is very common over open water. The wind velocity is assumed to be 40 kts. As seen, without the evaporation duct, the radar is able to detect a target up to the radar horizon of 38 km. However, in the presence of a 30 m evaporation duct, the clutter returns increase to the point where it buries the target signal at ranges beyond 20 km. An MTI processor would remove most of the clutter (25-40 dB improvement factor), however, it may also introduce blind speeds at or near missile velocities, which is equally undesirable. A compromise in blind speeds is generally required if the search radar is to detect both aircraft and missiles, having different velocity profiles.

Figure 4-7 shows the S/N response of a medium range radar, similar to the Sea Giraffe. For these types of systems, the transmit power is much lower and the frequency much higher than the long range search radar, hence, the detectable range is significantly reduced. The upper graph shows the effects of clutter on the performance of the radar without an evaporation duct, while the lower graph introduces an evaporation duct of 30 m height. The clutter is based on wind velocities of 0, 10, 20, 30, and 40 knots. As seen, without evaporation ducting and wind velocities up to 10 knots, the radar can detect the target up to 20 km or so, although there are some holes in coverage due to multipath, as indicated by the sharp nulls in the response. The target signal becomes buried in clutter up to 18 km when the wind speed exceeds 30 km. In the presence of an evaporation duct, it is seen that the radar coverage is completely eliminated as clutter exceeds the target signal at all ranges. As before, an MTI processor would remove most of the clutter, but it would also likely prevent the Sea Giraffe from detecting enemy ships. The detection of ships is a primary function of the Sea Giraffe.

Over the horizon (OTH) radars could theoretically be used to support the detection of long range missiles, although there are practical limitations for CPF type applications. OTH propagation is achieved by two means: ionospheric reflection/refraction, and Earth diffraction. The former is referred to as the sky-wave type radar, and usually operates in HF band (3-30 MHz), providing a detection 'footprint [schleher] of 500-1800 nm, which is outside the operational range of the

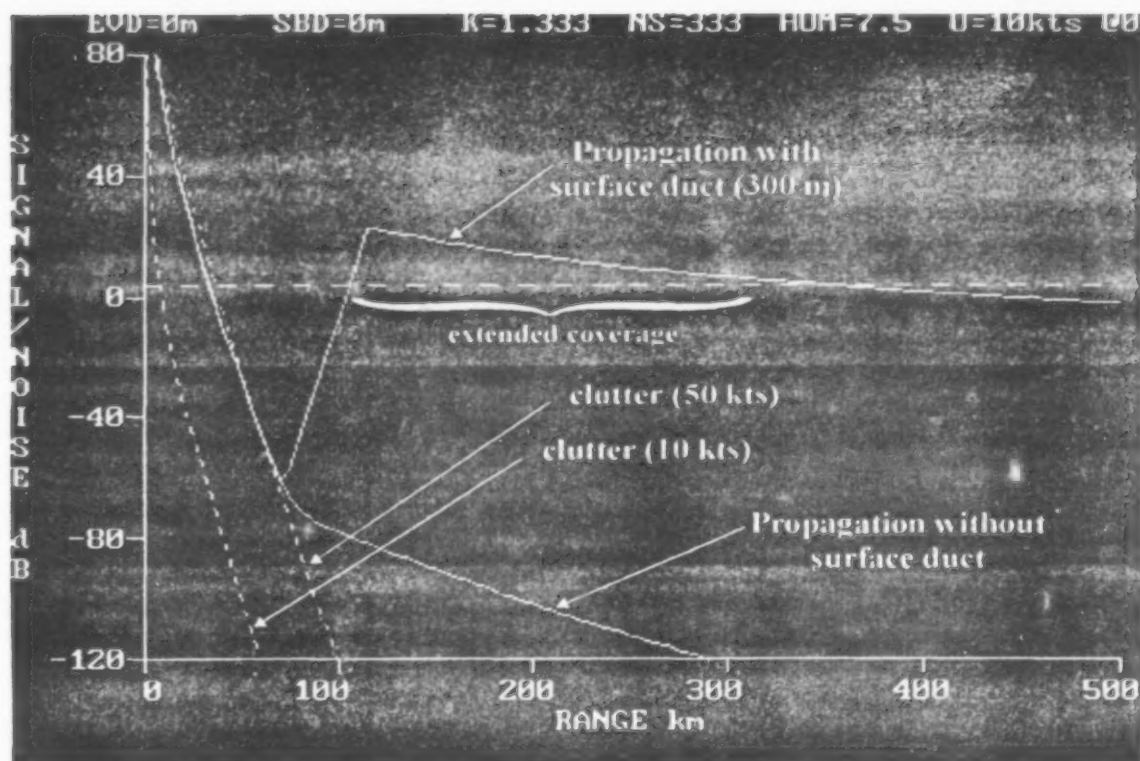


Figure 4-5

Extended range coverage of search radar due to surface duct

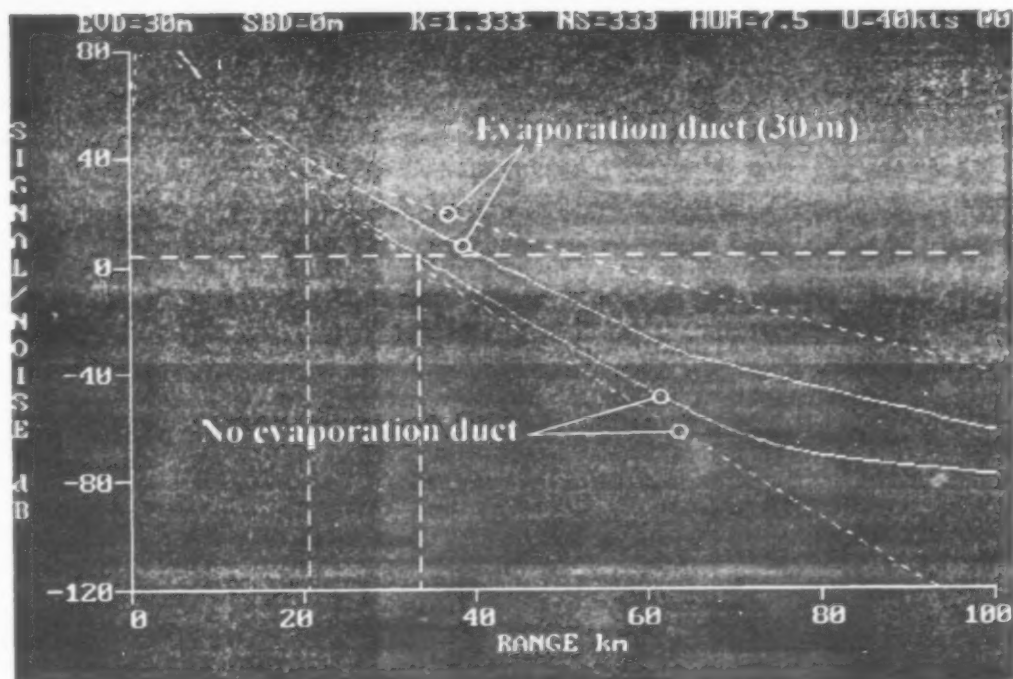
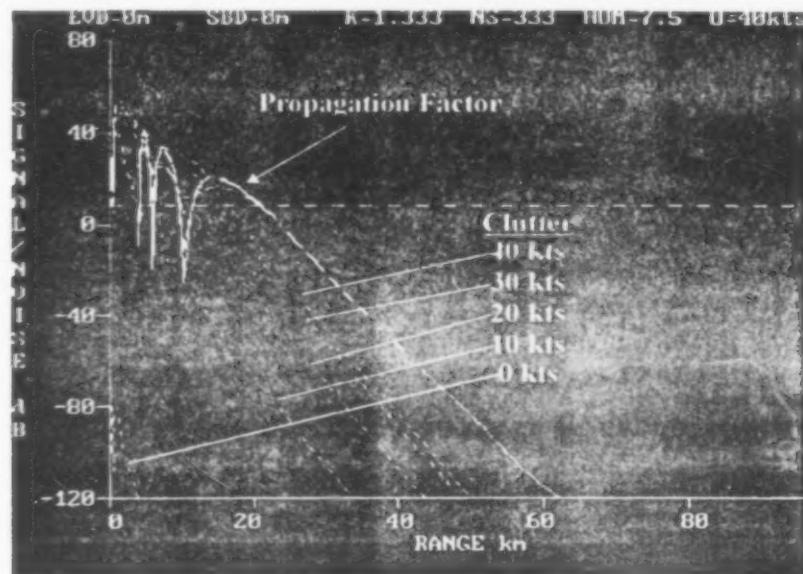
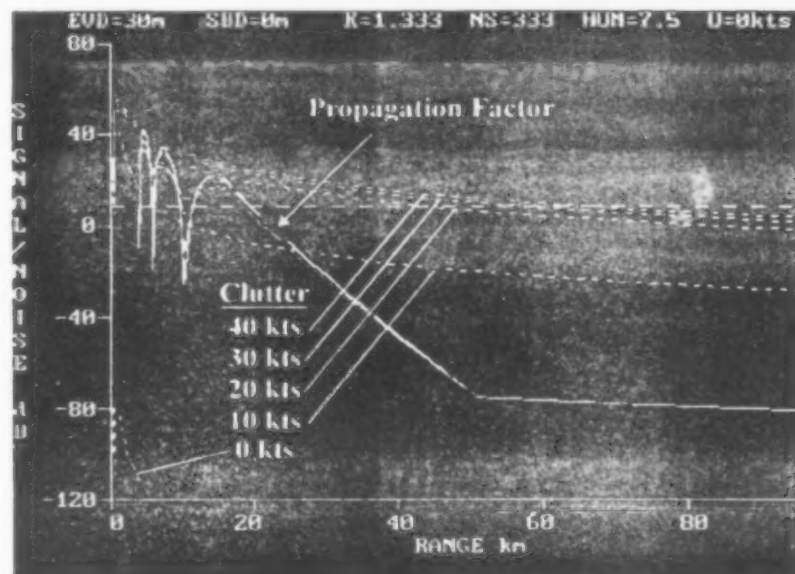


Figure 4-6

Effects of evaporation ducting on search radar



a) Effects of clutter without evaporation ducting



b) Effects of clutter with 30 m evaporation duct layer

Figure 4-7

S/N response for medium range search radar with clutter

CPF. The diffraction or 'ground-wave' OTH radar can provide coverage over a 200-400 km range. However, the primary limitations of this type of radar is that it operates at extremely low frequency, requiring a very large antenna, and is susceptible to fading, making it unreliable for early warning/detection.

IRST

The IRST could be used to detect missiles at relatively close range, < 20 km. Its performance is severely degraded by precipitation such as rain and snow, and is completely hampered by fog.

ESM

The ESM represents the principal sensor for detecting radar guided missiles at long range. With typical receiver sensitivities on the order of -60 dBm, sensitivity is not the critical issue for the ESM - it is more so for the seeker which has to contend with a two-way propagation loss and clutter. Key propagation anomalies affecting the performance of the ESM system, particularly at long range, are refraction and multipath.

As discussed in chapter 3, multipath can cause the power level of the received signal to theoretically drop to zero or increase by 6 dB, depending on the relative geometry of the ESM antenna and missile and the condition of the sea. Multipath also affects the seeker, but in a slightly different manner since the target (own ship) it is tracking is distributed in height (as well as in width). A distributed target produces many principal reflections which vectorially combine to yield relatively shallow nulls in the total received signal. Consequently, it is possible for the ESM to encounter deep multipath fades (for a relatively smooth surface) and lose sight of the missile, while the seeker continues to see/track the ship.

Refraction, particularly ducting, can either enhance or degrade the performance of the ESM system, depending on the prevailing meteorological conditions. If both the missile and ESM antenna exist in the same duct layer, then it is possible for the ESM to receive more energy than would be possible under normal propagation conditions, thus enhancing range detection. On the other hand, if both systems are in different duct regimes, then it is possible for the ESM not to receive any seeker energy for certain missile ranges. Refer to figure 4-8 for a graphical depiction of the various paths the radar signal can travel depending on the heights and pointing angle of the seeker antenna. The EWCP will have to give consideration to these propagation anomalies to dynamically characterize the performance of the ESM system. In addition to signal enhancements/reductions, refraction also introduces elevation errors, which is not a problem since we are only concerned with missile detection at this stage.

Two systems designed to evade ESM detection include the low probability of intercept (LPI) radar, in which the radar transmits at significantly reduced power levels over an extremely broad frequency bandwidth, and the anti-radiation missile (ARM), which passively tracks the ship's radar signals. LPI seekers are not yet common place, although they are expected to become more

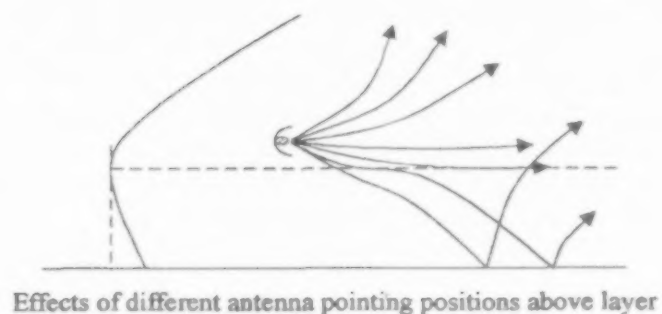
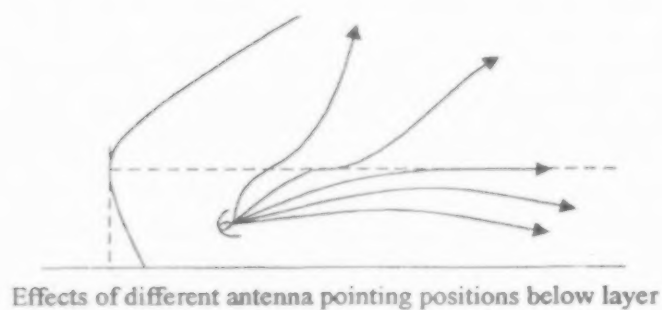
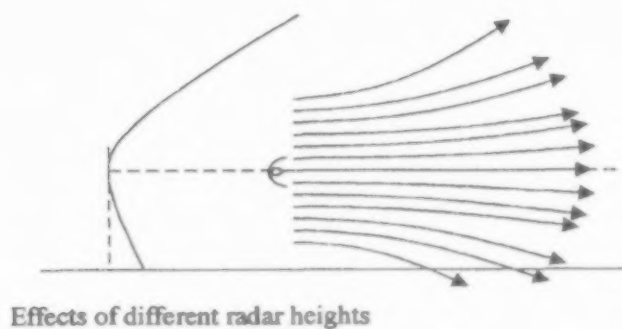


Figure 4-8

Effects of trapping layer for different geometries

prevalent in the future as the cost of the technology to implement them decreases. The key features of a LPI radar are spread-spectrum transmissions and low antenna sidelobes.

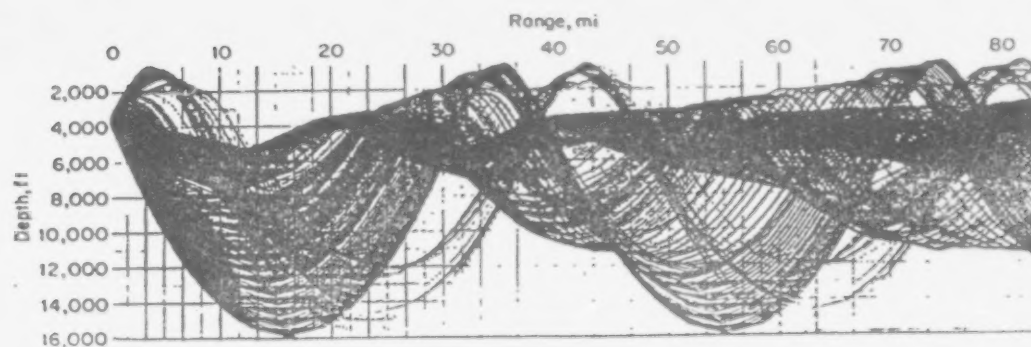
An ESM type system, with special provisions, could possibly detect missiles which are either not using conventional active radars for guidance, or only turn on their radar at the very last moment prior to impact, by measuring signals emanating from their altimeter. This assumes the missile employs an active altimeter as opposed to a barometric or infrared type. ARMs typically use barometric altimeters, as they fly at extremely high altitudes and therefore can tolerate inaccuracies associated with barometric measurements. Low altitude missiles, on the other hand, require more precise height measurements to avoid colliding into the sea and/or sea waves.

Typical power levels for active radar altimeters are on the order of 5 watts. Assuming an antenna gain of 0 dB for the altimeter antenna, and assuming it operates at 9 GHz, the level received by the ESM would be -110 dBm for a missile range of 25 km. The ESM antenna gain is assumed to be 10 dB. It is obvious this signal would not be detected by conventional ESM systems with sensitivities on the order of -60 dBm. Clearly, for the ESM to measure such minute signals, its receiver bandwidth would have to be reduced considerably to yield higher sensitivities. Additionally, a narrower antenna beamwidth would provide a higher gain at boresight. With these provisions, the ESM system would have to be accurately programmed with the threat altimeter's operating frequency, and to some extent, its antenna would have to be pointing in the general direction of the missile to receive the altimeter signal. This may not be practical from an operational point of view.

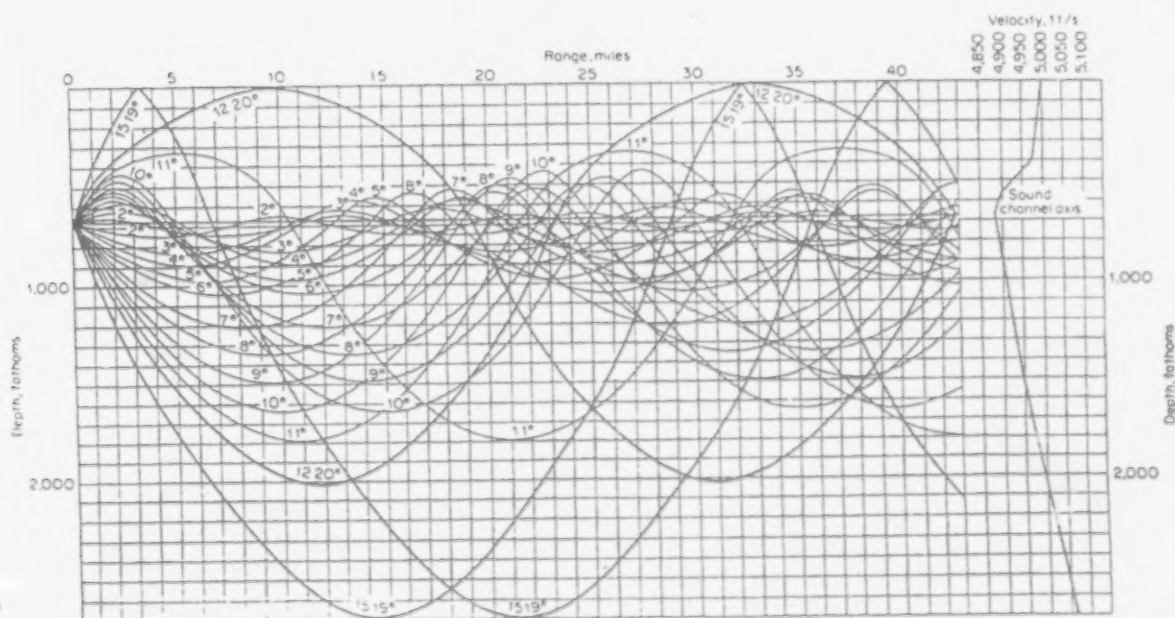
Sonar

Acoustic sensors may be used to detect the launching of missiles or torpedoes from submarines through transient analysis. The technology is currently available to measure acoustic 'spikes' or transients associated with subsurface launches originating hundreds of kilometres away in the ocean. Although the primary function of sonars is to detect disturbances below the surface, there is a possibility they could also be used to measure missile noise vibrations that couple into the water. Typical bandwidths for acoustic sensors towed behind ships are on the order of 100 Hz, hence, the reverberation associated with missile launch and flight must be sufficiently prominent at or below this frequency. The technique of measuring air-to-water acoustic coupling warrants further investigation to determine its potential use for early detection of missiles for the EWCP.

A principal factor affecting the performance of acoustic sensors is the presence of convergence zones, which defines the propagation of the acoustic signal through the water, as shown in figure 4-9 for a sound source at a depth of 4000 ft. Figure (a) is a hand drawn ray diagram from World War II, while figure (b) presents a computer simulation version. If the acoustic sensor is in a null of a convergence zone, then it will not measure any noise originating from the disturbance. Convergence zones are difficult to predict and characterize over time, hence, their effects cannot be easily overcome.



a) For source near the axis.



b) For source on the axis.

Figure 4-9
sound, 1967]

Example of convergence zones [R. Urick, principles of underwater

Another factor affecting the performance of the acoustic sensor is the amount of disturbance present in the water. The energy levels associated with the coupling of missile engine noise into the water will be extremely low, and may be completely masked by the hull noise of other ships in the vicinity.

4.1.2 Targeting Radar Mode Change

A targeting radar that changes modes may provide a clue to the EWCP that the current ECM technique is having success against the enemy radar operator. Parameters which may be changed include frequency, antenna scanning rate and pattern, PRI, etc. The only sensor that can be used to detect radar mode changes is the ESM system.

Factors influencing the performance of the ESM system include: environmental disturbances such as multipath and refraction, and multiple threat environment.

4.1.3 Third Party Radar Mode Change

In some cases, an enemy third party platform, such as an aircraft, is used to perform the targeting function, in which the coordinates of own ship are relayed back to the launch platform for missile designation. For certain third party platforms, the radar changes modes when the targeting data is transmitted, usually in the form of an altered PRI, providing strong evidence a missile attack is imminent. The ESM system would be used to detect these radar mode changes to alert the NEWCP. If no radar mode changes are detected, it may suggest that a missile designation has not occurred, and therefore, no missiles have been launched. This assessment, of course, depends on accurate intelligence regarding the launch platform's use of a third party targeting platform and the targeting radar changing modes during the transmission of targeting data.

The ESM system is potentially vulnerable to refraction, and a dense threat environment.

4.2 False Target Acquisition

The goal of this ECM technique is to cause the search radar to detect a false target and pass along its coordinates to the missile for pre-launch target designation. The result of this ECM should cause the missile to go off-course and miss own ship. False targets can be generated by either an onboard jammer or with confusion decoys. If a jammer is used and is successful in decoying the targeting radar, then the missile will have nothing to acquire when it initially turns on its seeker to search for own ship. At this point, if the ship is outside the missile seeker's field of view (FOV), then the ship would not be detected and the missile would either fly into the water or self-destruct after a pre-determined time. On the other hand, if the ship is still within the seeker's FOV, then there is potential for the missile to acquire the ship. Confusion decoys are employed at this stage to prevent seeker acquisition.

4.2.1 Onboard Jamming

False targets in sidelobes (FTS) is an onboard jamming technique used to create false targets in the PPI scope of an enemy search radar. FTS can be transmitted in a delayed or undelayed manner. In the undelayed mode, all the false targets are placed at the same range as own ship, as viewed on the PPI scope. The delayed FTS technique, on the other hand, positions the false targets at different ranges, making it more difficult for the operator to discern the true location of own ship. The ultimate goal of this ECM technique is to produce missile heading errors, so that the missile ends up flying into the water or self destructing. An additional effect which can be observed is the seeker antenna scanning as it searches for the target ship.

4.2.1.1 Missile heading error

Since the onboard jammer produces many false targets at various bearings, with respect to own ship, it is not possible to predict which false target the enemy designated for missile attack when ECM is successful. Consequently, the exact heading error cannot be predicted to help in the effectiveness assessment process. At the very least, the NEWCP, in conjunction with the jammer, should be able to estimate the position of the closest false target to the ship, so that a minimum heading error can be calculated (the position of the false target is, among other things, a function of the targeting radar antenna's scan rate). Note that false targets are usually placed on both sides of own ship with potentially different minimum ranges. Since jamming is applied against the targeting radar, which then sends the coordinates of the false target to the launcher, the trajectory error is inherent in the missile's flight from launch. Therefore, if a trajectory error is not measured in the early stages of flight, then jamming is not considered successful.

One possible ambiguity that may occur in the assessment is mistaking a pre-programmed flight manoeuvre for heading errors resulting from jamming. The EWCP will have to deal with this uncertainty.

The following sensors can be used to support the measurement of a missile heading error; active radar, PESM (if seeker is an active radar), and IR tracker.

Active Radar

An active radar can be used to measure the position of the missile over time to detect heading errors. For early indication, the following performance criteria apply: high angular accuracy, high transmit power to measure the echo returns from the missile's head-on RCS, and effective clutter cancellation for positive S/N. The latter suggests a coherent radar which can reject clutter returns through doppler filter banks.

The accuracy required to measure heading errors over time are shown in table 4.1 for a false target placed 5 km from own ship. Figure 4-10 depicts the scenario from which these accuracy numbers are derived. In this example, the targeting radar is situated 150 km away from own

ship, and the missile velocity is assumed to be 330 m/s. Note that although ECM is applied to the targeting radar, the effects are measured against the missile.

Table 4.1 Required angular accuracy for heading error measurements.

Missile Range (km)	Time (seconds)						
	1	5	10	15	20	30	50
50	0.0379	0.1946	0.404	0.628	0.869	1.409	2.807
25	0.152	0.803	1.724	2.793	4.045	7.323	20.36
15	0.421	2.299	5.19	8.913	13.837	29.838	n/a

There are a number of factors which define the angular accuracy of the radar including; antenna pattern, discriminant circuit, servo noise, and mechanical backlash. The SPS-49 has an angular accuracy of <B2> deg in azimuth, the Sea Giraffe has <B3> deg accuracy, and the STIR has <B4> deg accuracy. It is anticipated in the future, the multi-function radar (MFR) will have an accuracy of <B5> deg, while a LPI system will only have an estimated accuracy of <B6> deg. Clearly, the SPS-49 represents the best radar aboard the CPF today to measure heading errors with the most accuracy at relatively long range.

As shown in figure 4-10, the expected power received from reflections off a missile 30 km away with an antenna radius of 0.2 m is approximately -80 dBm - the pertinent parameters are also shown in the figure. The receiver sensitivity for the SPS-49 is <B7> dBm, <B8> dBm for the Sea Giraffe, and <B9> dBm for the STIR. The transmit powers are <B10> kW for the SPS-49, <B11> kW for the Sea Giraffe, and <B12> kW for the STIR. Based on this, the SPS-49 radar is likely to be the first system aboard the CPF to detect a missile.

The effects of clutter cannot be ignored. Since the radars operate at low grazing angles, the clutter size is essentially dictated by the area illuminated by the radar antenna pattern. The formula defining the amount of power C received from area sea clutter is [skolnik]:

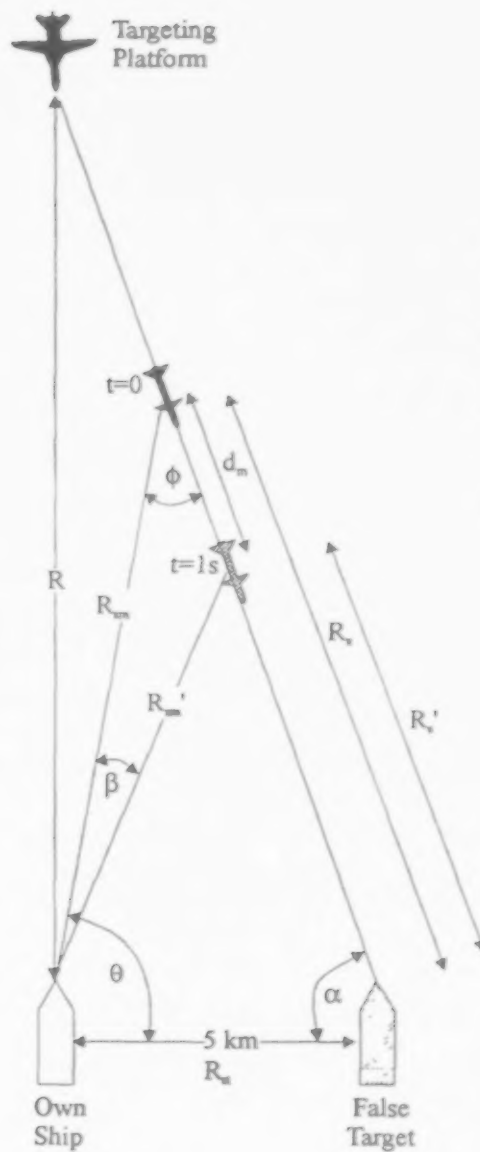
$$C = \frac{P_t G A_e \sigma^0 \theta_B (c\tau/2) \sec \phi}{(4\pi)^2 R^3}$$

where,

P_t = transmit power

G = gain of antenna

σ^0 = mean cross section of clutter per unit area



Assume $V_m = 330$ m/s, $R = 150$ km.

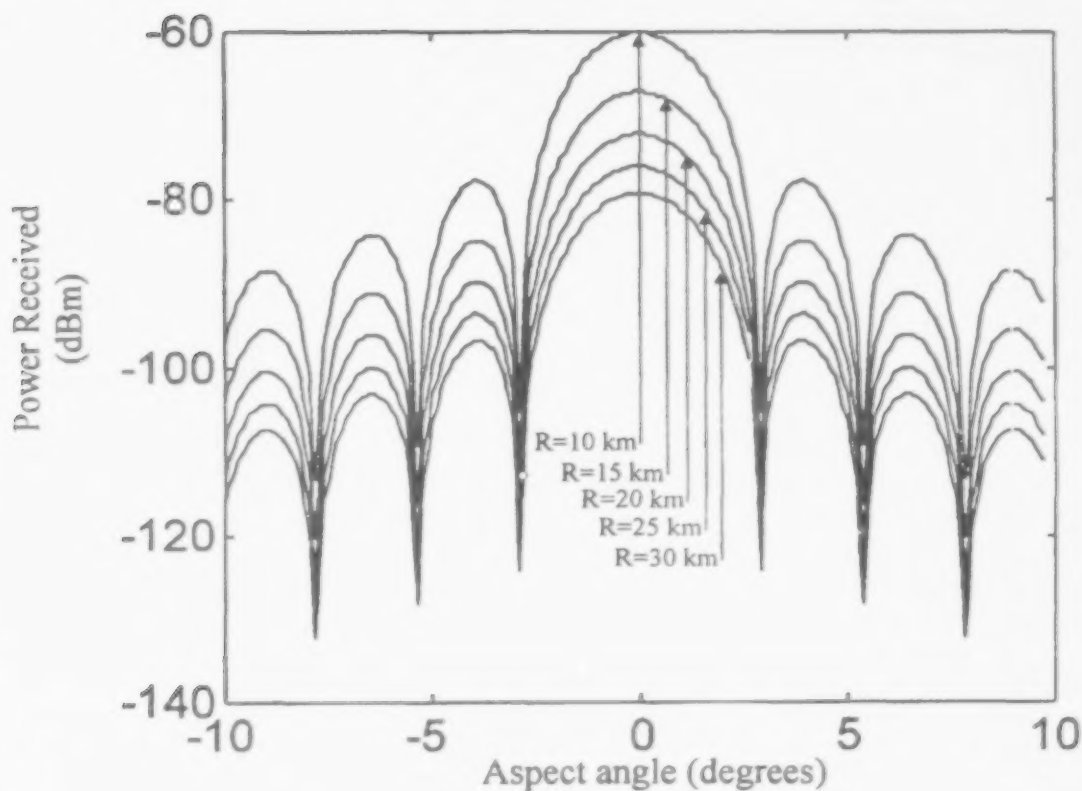
$$\phi = \sin^{-1} (5/R_m \sin \alpha)$$

$$R_m'^2 = (R_m^2 + d_m^2 - 2 R_m d_m \cos \phi)$$

$$\beta = \sin^{-1} (\sin \phi .33t / (R_m^2 + (.33t)^2 - .66 R_m t \cos \phi))$$

Figure 4-10

Example scenario to illustrate required angular accuracy of radar.



λ	ψ_r	θ (deg)	ρ	a (m)	f (GHz)	G (JD radar)	P_t (kw)	R (km)
.033 m	90	-10-10	0.333	0.2	9	1000	100	10-30

Figure 4.11

Structural mode response of seeker antenna at different ranges

θ_b = azimuth beamwidth of radar antenna
 c = velocity of propagation
 τ = pulse width
 ϕ = grazing angle of radar antenna

Clutter is dependent upon the condition of the sea including: wave height, wind speed, direction of the waves, etc., and also on the operating parameters of the radar, including frequency, polarization, and grazing angle.

Maritime multipath will affect the performance of the radar in terms of received power, as discussed already. In terms of angle tracking, multipath introduces relatively little error in azimuthal measurements - perhaps some noise type disturbances due to minute lateral reflections off large waves such as sea swells. On the other hand, multipath arising from neighbouring ships or other obstacles may introduce significant errors in azimuth readings which cannot be ignored. Maritime multipath can create significant elevation errors, which is of no concern here except, perhaps, for coupling effects which could occur between the elevation and azimuth channels through the antenna feeds. The cross-coupling phenomenon represents a problem for very fine angular measurements, perhaps on the order of 1 degree or less. This will have to be analyzed further for specific radar equipment.

The disadvantage of using a radar for effectiveness assessment is it may serve to beacon the missile, or at the very least, broadcast the precise location of own ship to the enemy's targeting platforms. Furthermore, the radar cannot be used during EMCON conditions.

PESM

A precision ESM system with a high accuracy direction finder (HADF) could be used to measure fine angular movements of the missile, providing the seeker is active. An angular accuracy of 0.1 degree is expected, which makes the HADF ideal for the types of measurements required. Receiver sensitivity is not an issue for measuring missile energy, unless the missile is equipped with a LPI radar, as discussed earlier for ESM.

The primary disadvantage of a PESM system is that it can only be utilized against active seekers.

IR Tracker

An IR sensor could be used to measure missile heading errors. An IR tracker is more desirable over an IRST system, as it can give angular measurements immediately and uninterrupted, while the IRST scans at a relatively slow rate (typically 3 s/rev or so), and usually must make contact with the missile two or three times before declaring a valid track. The angular accuracy provided by an IR sensor is superior over a radar, usually on the order of 0.1 degree. The primary weakness of the IR sensor is it operates over short range (20 - 30 km), and requires clear weather - precipitation severely degrades the performance of the IR sensor, while fog renders it

completely inoperable.

4.2.1.2 Seeker antenna scanning

A seeker antenna that continues to scan is a strong indication that the missile has not acquired own ship (an ambiguity may occur with missiles which perform a search while track function). This hypothesis is further reinforced if a missile heading error is simultaneously measured. The ESM system is the primary sensor for measuring antenna scans (a radar could also be used, but not as effectively). If the ship is outside the seeker's FOV, then the ESM will measure the energy transmitted through the seeker antenna sidelobes. Typical sidelobe levels for a uniformly illuminated circular aperture antennas, with respect to the mainlobe, are -15 dB for the first lobe, -23 dB for the second lobe, and -28 dB for the third lobe. For typical seeker output power levels of 25 and 100 kW, and antenna gain of 30 dB for the seeker and 10 dB for the ESM system, the following power levels can be expected at the ESM receiver for various ranges of the missile, based on the formula of $P_{rec} = P_t G_t G_r \lambda^2 / (4\pi R)^2$:

Table 4-2 Sidelobe levels of seeker power

Missile Range (km)	Seeker Mainlobe response (dBm)		1 st lobe response (dBm)		2 nd lobe response (dBm)		3 rd lobe response (dBm)	
	Tx=25 kw	Tx=100 kw	Tx=25 kw	Tx=100 kw	Tx=25 kw	Tx=100 kw	Tx=25 kw	Tx=100 kw
50	-32	-26	-47	-41	-55	-49	-60	-54
25	-26	-20	-41	-35	-49	-43	-54	-48
10	-18	-12	-33	-27	-41	-35	-45	-39

For the levels shown in the table, the ESM with a receiver sensitivity of -60 dBm, should have no difficulty in measuring the sidelobe energy of the seeker to detect antenna scanning. A seeker that continually scans may provide an indication that the missile is not performing a pre-programmed trajectory change, but is instead searching for the target.

4.2.1.3 Missile Defeated

The following can be used to support the assessment of a missile being defeated, i.e. self destructing or flying into the water: Crewman, IRST, and Radar.

For both crewman and IRST, the weather has to be relatively clear. In the case of the IRST, an operator would have to make the judgement that the missile was defeated once track was broken and the missile could not be detected again. Certain radars, such as the CPF's STIR, are equipped with algorithms to detect a sudden change in missile velocity and acceleration, which would automatically indicate the missile has been defeated.

4.2.2 Offboard false targets

Offboard false targets can be in the form of confusion chaff, rubber ducks, and active offboard decoys. If the decoy is successful against the targeting radar, then the missile should acquire the decoy the moment it activates. Unlike the onboard generated false targets, discussed above, offboard decoys should produce a predictable and consistent missile heading error that coincides with the current decoy deployment. Additionally, if the decoy is successful, the seeker should not continue to scan, as it would for false targets generated by the onboard jammer.

The following ECM effects should occur: missile heading error, chaff reflections, AOD confirmation, and targeting radar mode change.

4.2.2.1 Missile heading error

The following sensors can be used to support the measurement of a missile heading error;

- active radar
- PESM (if threat uses active radar)
- IRST (staring type)
- consistent with decoy geometry

4.2.2.2 Chaff reflections

The ESM system would be the principal sensor for measuring chaff cloud reflections. A HADF system could also be used to measure the spatial distribution of the signal to ensure it is consistent with that of a chaff cloud.

Although confusion chaff is designed to counter the targeting radar, its results are primarily measured against the missile. ECM success is declared the moment the seeker turns on and acquires the chaff cloud.

The following equation applies in determining the received power at the ship from bi-static chaff reflections [skolnik]:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma_c}{(4\pi)^3 R_{sc}^2 R_{mc}^2 L_{mc}(t) L_{sc}(r)}$$

P_t = transmit power (100 kw)

G_t = transmit antenna gain (30 dB)

G_r = receive antenna gain (10 dB)

λ = wavelength (0.03 m)
 σ_c = bi-static RCS
 R_{sc} = range between ship and chaff
 R_{mc} = range between missile and chaff
 $L_{mc}(t)$ = propagation loss for R_{mc} (1)
 $L_{sc}(r)$ = propagation loss for R_{sc} (1)

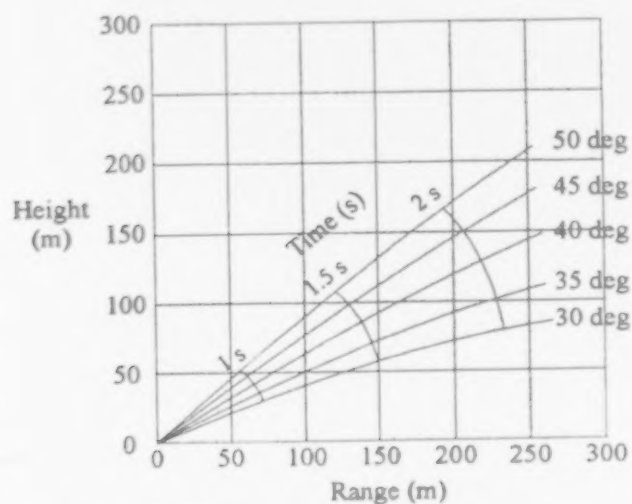
The actual calculation of σ_c is complex and its derivation is well outside the scope of this study, as discussed in section 3.4. Nevertheless, several values of σ_c can be explored to gain insight into the types of power levels expected for various missile ranges and chaff deployment tactics. The parameters in brackets represent default values. Since the chaff is used in the confusion mode, it is assumed the chaff cloud is fully bloomed by the time the seeker turns on to search for its target.

The SHIELD II chaff/flare launchers are typically set at fixed bearings of $\pm 30^\circ$ and $\pm 110^\circ$. Elevations vary from 30° to 50° . The chaff rocket burns for approximately 1.2 seconds with an average acceleration of 130 m/s^2 (13 g's). Figure 4-12(a) depicts the deployment ranges of SHIELD II chaff for different elevation launch angles. As shown, a maximum deployment range of 300 m is obtained at an elevation launch angle of 50° . Figure 4-12(b) depicts the chaff RCS bloom versus time. Two curves are presented, one for free space measurement, and the other with 6 dB enhancement due to multipath (when the direct and indirect signals add constructively). As indicated, a maximum RCS of 42 dBm^2 (16000 m^2) can be obtained after 30 seconds from initial chaff cloud burst.

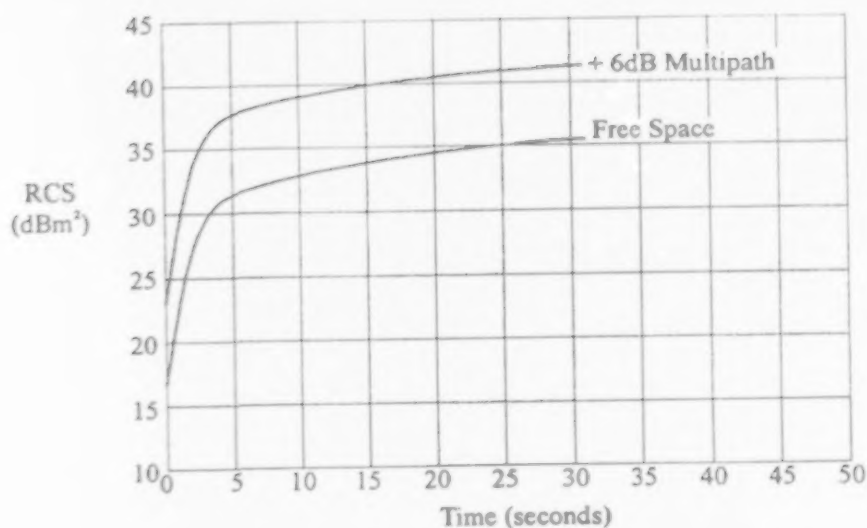
Figure 4-13 depicts the expected power responses for chaff deployment distances of 100, 200, 300 m, and 400 m from the ship, with $\sigma_c = 10000 \text{ m}^2$. As seen for a missile range of 30 km, the bi-scattered power is approximately -37 dBm for $R_{sc} = 200 \text{ m}$, and approximately -42 dBm for $R_{sc} = 400 \text{ m}$. Figure 4-14 presents two graphs of power responses for chaff deployment ranges of 100 m and 400 m, for different values of σ_c ranging from 1000 to 15000 m^2 . As shown, for a chaff cloud distance of 400 m from the ship, and a bistatic RCS of 1000 m^2 , the ESM system is expected to receive approximately -50 dBm of power. A typical receiver sensitivity for an ESM system is about -60 dBm ($1 \text{ } \mu\text{W}$) over a wide range of frequency, therefore, the ESM system should easily detect chaff cloud reflections for typical deployments.

4.2.2.3 AOD Confirmation

In the case where an active offboard decoy (AOD) is used, ECM success may be inferred if signals emanating from the sidelobes of the decoy antenna match those of the seeker. The belief of success is reinforced if a corresponding missile trajectory deviation is measured, or if energy received directly from the missile does not increase at a rate consistent with typical missile speeds, suggesting the seeker is tracking the decoy. The ESM system would be used to measure and compare sidelobe energy from the decoy with the direct signal of the missile.



a) Chaff trajectories



b) Chaff RCS bloom

Figure 4-12

SHIELD II chaff characteristics

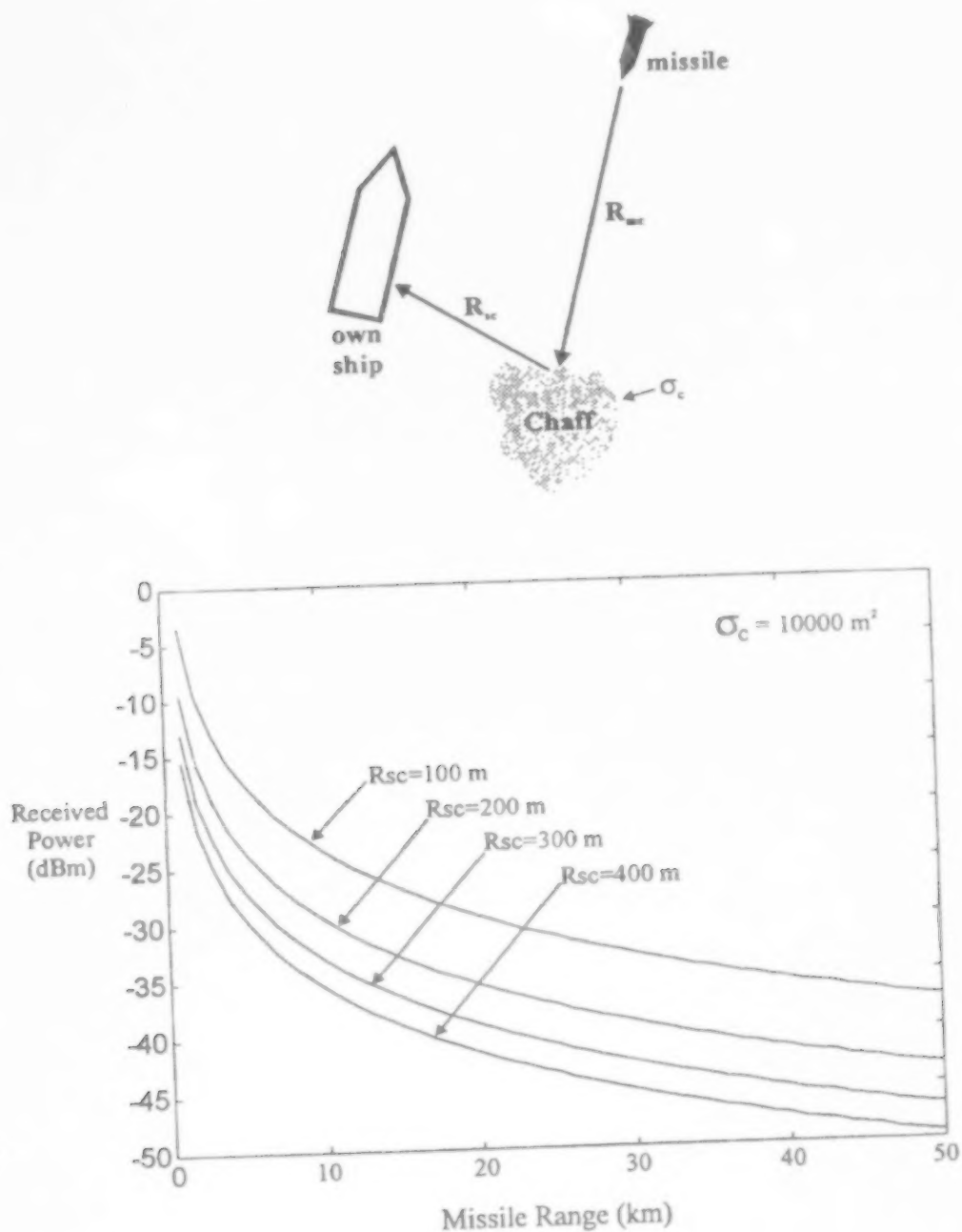


Figure 4-13

RCS response for different chaff deployment ranges

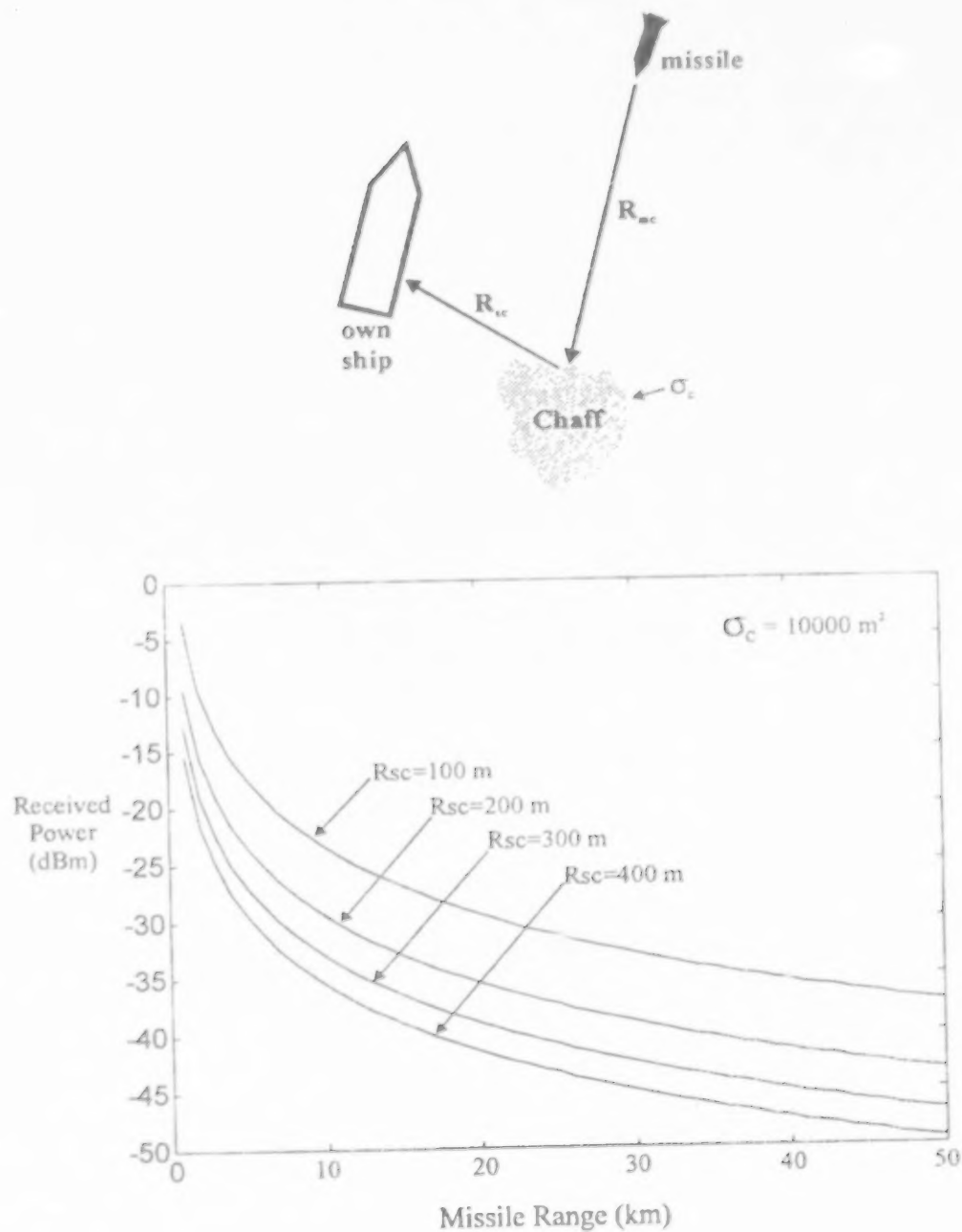
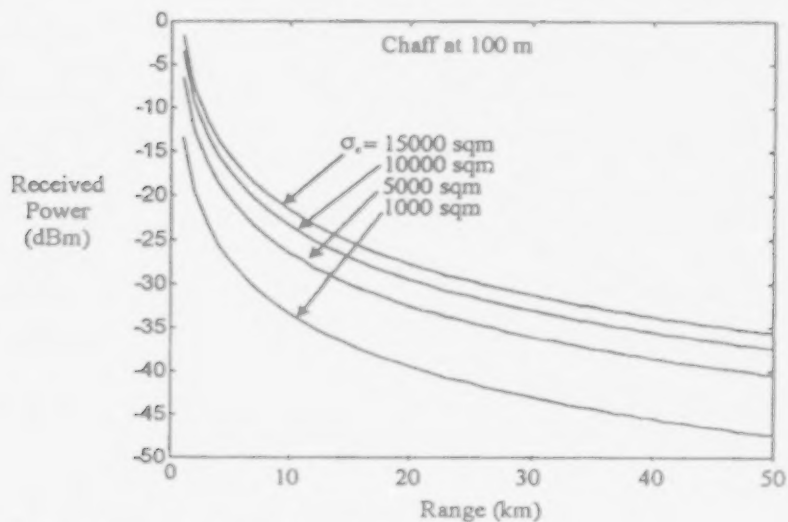
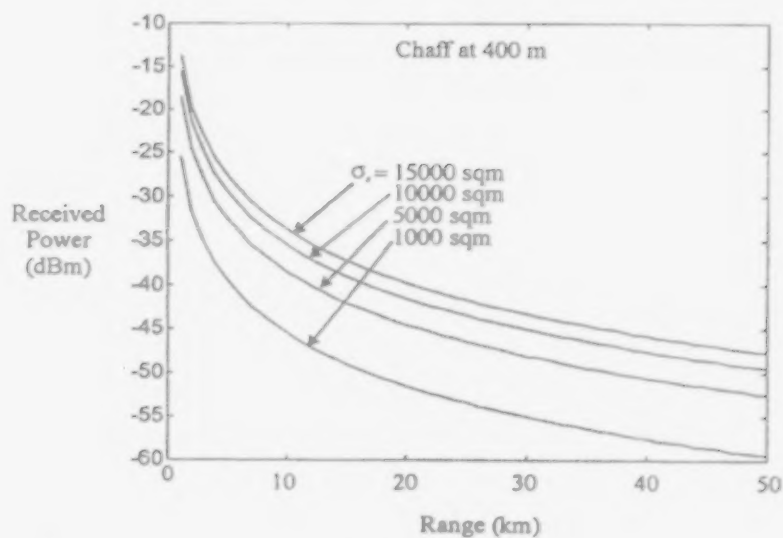


Figure 4-13

RCS response for different chaff deployment ranges



a) Chaff launched 100 m from ship



b) Chaff launched 400 m from ship

Figure 4-14 Power received from chaff reflections for different chaff ranges and bistatic RCS

Another means of determining if the AOD is engaging the missile is to receive a confirmation signal from the decoy. The signal would be extremely low in power to avoid detection by hostile sensors, and perhaps encoded spectrally, so that only own ship can receive and decipher the signal. A specially tailored transmitter/receiver would be used to facilitate this process. The AOD could also pass along the power levels it receives from the missile, to help the EWCP determine if the missile is indeed pursuing the decoy.

4.2.2.4 Search Radar Parameter Changes

Confusion chaff may force the operator to alter radar parameters to discriminate against jamming. The radar mode change may occur through antenna scanning, frequency, and/or PRI. The ESM is the only sensor that would be used to detect radar parameter changes.

Factors influencing the performance of the ESM system include: environmental disturbances such as multipath and refraction, and possibly a dense emitter environment.

5.0 Effectiveness Assessment for Missile Seekers

The purpose of this section is to address high level effectiveness assessment for those ECM techniques that are directed against missile seekers. Such techniques accomplish a variety of tactical objectives including the following:

- (a) Detection denial;
- (b) Seeker acquisition of false targets;
- (c) Disruption of the tracking activities of the seeker;
- (d) Disruption of the tracking activities of the seeker / seeker acquisition of false targets; and
- (e) Seduction of seeker tracking gate onto decoy.

The first two techniques listed above are targeted against threat seekers that are in the search phase of their operations whereas the latter three techniques are directed against threats which have achieved a lock-on state.

There are a variety of challenges to be overcome when assessing the effectiveness of such countermeasures. In particular, efforts to measure effectiveness as well as to generate a predicted response are problematic. Threat characteristics and manoeuvres, sensor limitations, environmental effects, as well as imperfect intelligence information all have direct bearing on high level effectiveness assessment.

Certain threat characteristics may introduce ambiguity into the effectiveness assessment function. Measured changes in threat trajectory may have effectiveness assessment value, yet such changes in direction can possibly represent pre-programmed threat manoeuvres. Changes in threat trajectory may be measured directly by tracking the target with a sensor or indirectly by such methods as measuring seeker doppler shift or cross-pol / co-pol characteristics. In addition, modern ASM threats frequently have very short search periods. This threat characteristic places severe limitations upon the capability of the NEWCP to assess the effectiveness of countermeasures targeted against the threat seeker's search phase. Finally, radar mode changes induced by ECM may be ambiguous to those associated with "normal" mode transitions on the part of the threat;

High speed (possibly sea-skimming) threats impose severe temporal constraints upon effectiveness assessment activities. The threat may activate its seeker at relatively close range and little time may be available to assess the effectiveness of countermeasures in order to allow other defensive options to be implemented. It should be remembered that there is no value in performing effectiveness assessments if there is no possibility of taking subsequent action.

The inherent inaccuracies of various sensors are another source of uncertainty in assessing countermeasure effectiveness. Such inaccuracies introduce an element of ambiguity concerning the measurement of trajectory deviations. Many EW deployments will induce relatively small angular changes to threat heading. Even if the EW countermeasure causes a change to trajectory, some time may be required before the change in threat angular position, as measured from the ship, can be distinguished from the effects of sensor "noise" in the measurement of angular position. Unfortunately, available time can be at a premium in engagements involving high-speed modern ASMs.

Environmental effects also contribute to the complexity of the effectiveness assessment problem. For example, multipath effects can mimic the presence of chaff reflections and the occurrence of seeker jogs, both of which have significant effectiveness assessment value.

As discussed in chapter 2 of this report, effectiveness assessment consists of comparing measured threat response to that response that is expected, should the countermeasure achieve its objective. As discussed above, there are a variety of factors that introduce ambiguity into the measurement of events / phenomena with effectiveness assessment content. Similarly, the generation of an expected response for a particular EW deployment is not without its own ambiguities. Predicted threat responses rely heavily on intelligence information concerning the capabilities and characteristics of threat seekers. Should such information be false or inadequate, effectiveness assessment can be compromised. One particular concern deals with the EPM characteristics of the threat. There can be a strong correlation between expected threat response and the inferred EPM attributes of the threat seeker.

The challenges associated with the measurement of phenomena to support effectiveness assessment give rise to a requirement to generate the most comprehensive and accurate tactical picture possible. A sensor data fusion capability will help meet this need. Consider, for example, the use of seduction chaff to prosecute a threat that is in lock-on mode against ownship. In order to measure a threat trajectory deviation induced by the chaff, measurements from a variety of sensors can be integrated to provide the most accurate and complete positional characterization of the threat. Furthermore, data fusion techniques can be used to associate the reflected signal from a chaff cloud with a particular threat, thus enhancing effectiveness assessment capabilities.

Refer to Figure 5-1 for an illustration of the different effectiveness assessment techniques that could support various EW techniques for the prosecution of threat missile seekers. Low level effectiveness assessment techniques addressed in this study include: i) missile trajectory deviations, ii) radar mode changes, iii) chaff reflections, and iv) antenna jogs. In order to produce a high level assessment of ECM effectiveness, the results of all relevant low level effectiveness assessment techniques are integrated together. Whereas an individual low level technique might not provide convincing evidence of ECM effectiveness, it is possible that the combination of evidence from a variety of such techniques will render a more definitive assessment.

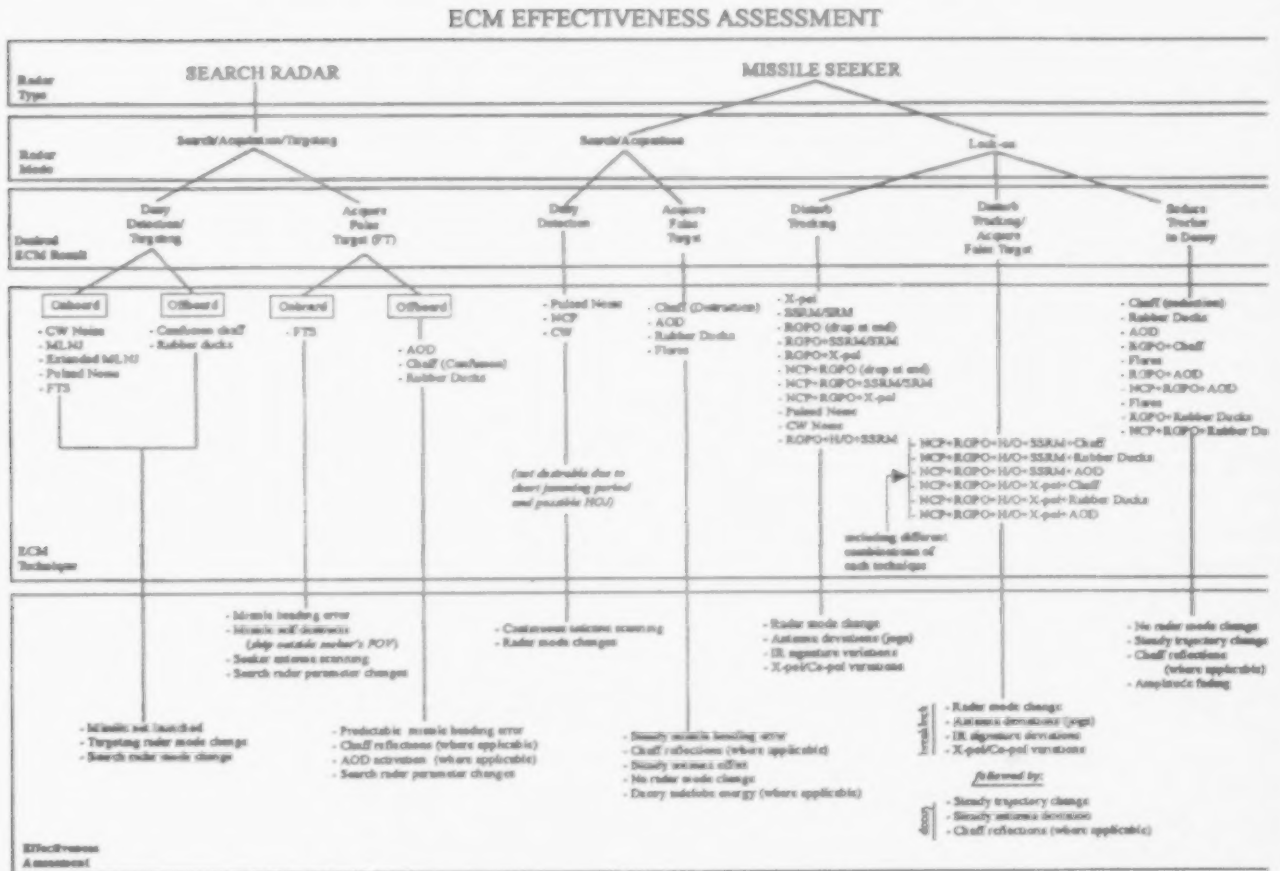


Figure: 5-1 Contextual Diagram for ECM Effectiveness Assessment

The requirement to integrate uncertain evidence from a variety of sources in order to arrive at a high level assessment of ECM effectiveness gives rise to a requirement to consider a variety of formalisms for dealing with such uncertainties. This requirement, addressed in detail in Section 7 of this report, will be a central NEWCP design issue.

The remaining material in this section is divided according to the five identified tactical objectives associated with the prosecution of threat missile seekers (refer above). For each tactical objective under consideration, the set of low level effectiveness techniques of relevance will be identified. For each technique thus identified, the capability of each sensor to support effectiveness assessment will be addressed. In so doing, the capabilities of the sensor suite to support effectiveness assessment will be addressed across a range of tactical objectives. As discussed elsewhere in this document, effectiveness assessment cannot be properly addressed without accounting for the high level context in which an arbitrary countermeasure is deployed.

5.1 Search / Acquisition Mode

As the missile approaches the radar horizon, it turns on its seeker to search for and autonomously track the target ship for final impact. If the initial targeting information was accurate and the missile's inertial guidance reliable throughout flight, then the ship should be situated well inside the seeker's field of view (FCV) at turn-on time - at which point the seeker acquires the ship relatively quickly. The acquisition process is so quick, in fact, that it leaves very little time for the jammer to acquire the seeker signal and execute the appropriate search ECM technique. In this case, the jammer may be operated in JAM IMMEDIATE mode, in which a CW signal is transmitted to interfere with the operation of the seeker, prior to the missile turning on. Offboard decoys can also be very effective providing they are deployed in sufficient time. An advantage the decoy has against the seeker in search mode, is that there are generally no operators in the loop to discriminate against ECM.

The two principal desired ECM results are target detection denial and false target acquisition.

5.1.1 Target Detection Denial

Target detection denial attempts to prevent the seeker from acquiring own ship by transmitting distracting electronic signals that mask the echo returns. This is done primarily by the onboard jammer, although, as just alluded to, the time allotted for jamming against this phase of the seeker is extremely short, and is generally not considered a viable tactic. Typical ECM techniques that can be applied against the search/acquisition phase of the seeker include CW and pulsed noise. It is important to note that there is a risk the noise may prompt the missile to enter into HOJ mode, which is undesirable. The ECM effects that can be measured/detected include: continuous seeker antenna scanning, and seeker mode changes.

5.1.1.1 Scanning of Seeker Antenna

For some missiles, if onboard jamming is successful against the search/acquisition phase of the seeker, the seeker's antenna will continue to scan as it attempts to locate own ship. For some of the older systems, the seeker may unwittingly lock onto the noise, resulting in spurious tracking and a possible miss-distance. For the more sophisticated systems, the seeker may enter into HOJ, and track the noise signal, as mentioned above. The ESM system represents the primary sensor for detecting antenna scans, while a radar may be used as a secondary sensor.

ESM

Since the missile is at relatively close range during this phase, <40 km or so for low altitude missiles, then sensitivity is not considered an issue regarding ESM performance. As well, with typical seeker antenna beamwidths on the order of 5° , and azimuth scans of $\pm 5^\circ$ for fine angular search, and $\pm 10^\circ$ for coarse angular search, the ESM will have no difficulty detecting the power fluctuations associated with antenna scanning. Typical scan rates for anti-ship missile are on the order of $5^\circ/\text{s}$. Considering a scenario whereby the seeker antenna is scanning coarsely ($\pm 10^\circ/\text{s}$), and assuming it takes at least 4 scans before the NEWCP can make an accurate assessment, implies a time lapse of approximately 16 seconds. For a typical missile velocity of 300 m/s, the missile will have travelled 4.8 km to a range of 34.2 km from own ship during the assessment process.

Multipath, under certain rough sea conditions, may cause some fading to resemble those associated with antenna scanning, however, the fades would occur randomly and hence, could be easily discriminated against over time.

Radar

A radar could be used to measure the bi-static scattering off the seeker antenna to determine if the antenna is scanning, as described in chapter 3 for jog detection. To achieve maximum reflections, the radar should operate out of the seeker's frequency bandwidth, and at orthogonal polarization with the seeker's antenna, yielding a condition known as structural mode response. It is necessary that the radar be a tracker, as opposed to a surveillance type, as the scanning rate of the latter system would be too slow. Given the above, the STIR radar would be suitable for achieving this type of measurement. With its transmit power levels, and the range at which it would have to operate to measure the bi-static reflections, the STIR should have no difficulty receiving the echo returns to detect the antenna scans. An advantage with using a radar, is that it has full control over the transmit parameters, which can be altered or diversified to overcome the effects of environmental disturbances such as multipath.

As with the ESM system, the assumption is made that the seeker antenna would have to complete 2 to 4 scans before the radar can make a determination, which is a reasonable time from an ECM deployment perspective.

5.1.1.2 Seeker Mode Changes

If noise is effective, it may force the seeker to alter its transmit parameters in its attempt to overcome the disturbance. An ESM system would be used to detect this mode change, signifying a possible success in ECM. Although ECM may have been successful in forcing a mode change, ship survivability may not have been enhanced if the missile continues to pursue the ship in HOJ mode. In this case, an alternative ECM deployment would be required, or at the very least, the jammer would have to momentarily stop transmitting noise. A common tactic is to turn on and off the noise signal repeatedly, forcing the seeker to alternate modes, ultimately leading to unstable tracking.

5.1.2 False Target Acquisition

The purpose of ECM against this phase of the threat is to force the seeker to acquire a false target rather than own ship. False targets may be generated through the deployment of decoys including dilution chaff, active offboard decoys, rubber ducks, and flares (for IR guided seekers). If ECM is successful, then the following should be detected: predictable steady missile heading error, chaff reflections (for chaff deployment), presence of decoy sidelobe energy, and no radar mode change.

5.1.2.1 Predictable Steady Missile Heading Error

If the seeker has acquired the decoy, then a steady, predictable heading error, consistent with the decoy geometry, should be measured, signifying ECM success. The following sensors could be used to measure trajectory deviations during false target acquisition of the missile: tracking radar, HADF, IR tracker.

Tracking Radar

A tracking radar can be used to measure the position of the missile over time to determine if it is heading for the decoy. Because of the relatively close range of the missile, <40 km, sensitivity is not an issue regarding performance. Clutter may pose a problem for non-coherent systems, depending on the condition of the sea and the operating parameters of the radar. Clutter is minimized when the radar operates at horizontal polarization. A tracking radar, as opposed to a scanning type, is necessary, to detect the deviation quickly given the short range and high speed of the missile. Multipath can cause elevation errors and possibly impede tracking if the missile enters into a propagation null. There is little that can be done, except perhaps to diversify the operating frequency so as to decorrelate the effects of multipath.

At this close range, angular accuracy and the time it takes for the decoy to separate from own ship are the key parameters determining radar performance. For chaff and flares, decoy separation is a function of, among other things, wind and ship speed and direction. Separation for active offboard decoys and rubber ducks are primarily determined by the ship's speed and

for active offboard decoys and rubber ducks are primarily determined by the ship's speed and direction (sea currents contributes only slightly).

Typical radar accuracy is on the order of 0.5° .

Figure 5-2 illustrates the time dependant angular difference between:

- (i) The angular position subtended by a threat that is radial inbound from $t = 0$ onwards; and
- (ii) The angular position subtended by a threat that has been deceived at $t = 0$ by a dilution chaff decoy deployed 1000 m from the ship.

This angular difference, which changes with time, is denoted as β . It is assumed both the ship and decoy do not move during the engagement. The seeker is assumed to be heading radially for the ship, until it turns on, at which point it alters its course and heads directly for the decoy. In this scenario, the missile, which is travelling at a speed of 600 m/s, turns on its seeker at a range of 25 km from the ship. For a radar accuracy of 0.5° , it can be seen that approximately 6 seconds are required for the trajectory deviation to exceed the accuracy of the sensor.

HADF

A HADF system represents an effective sensor for measuring minor heading changes of the missile as it pursues the decoy. Typical accuracies are on the order of 0.1° .

One disadvantage of the HADF approach is it only works with active radar guided seekers.

IR Tracker

An IR tracker can provide accurate measurements of missile heading changes to determine quickly if the missile is pursuing the decoy. For typical plume characteristics, the IR detector is effective up to ranges of 20-25 km under clear weather conditions. The IR has a typical accuracy of 0.1° , similar to the HADF system, hence, providing the same performance as the HADF.

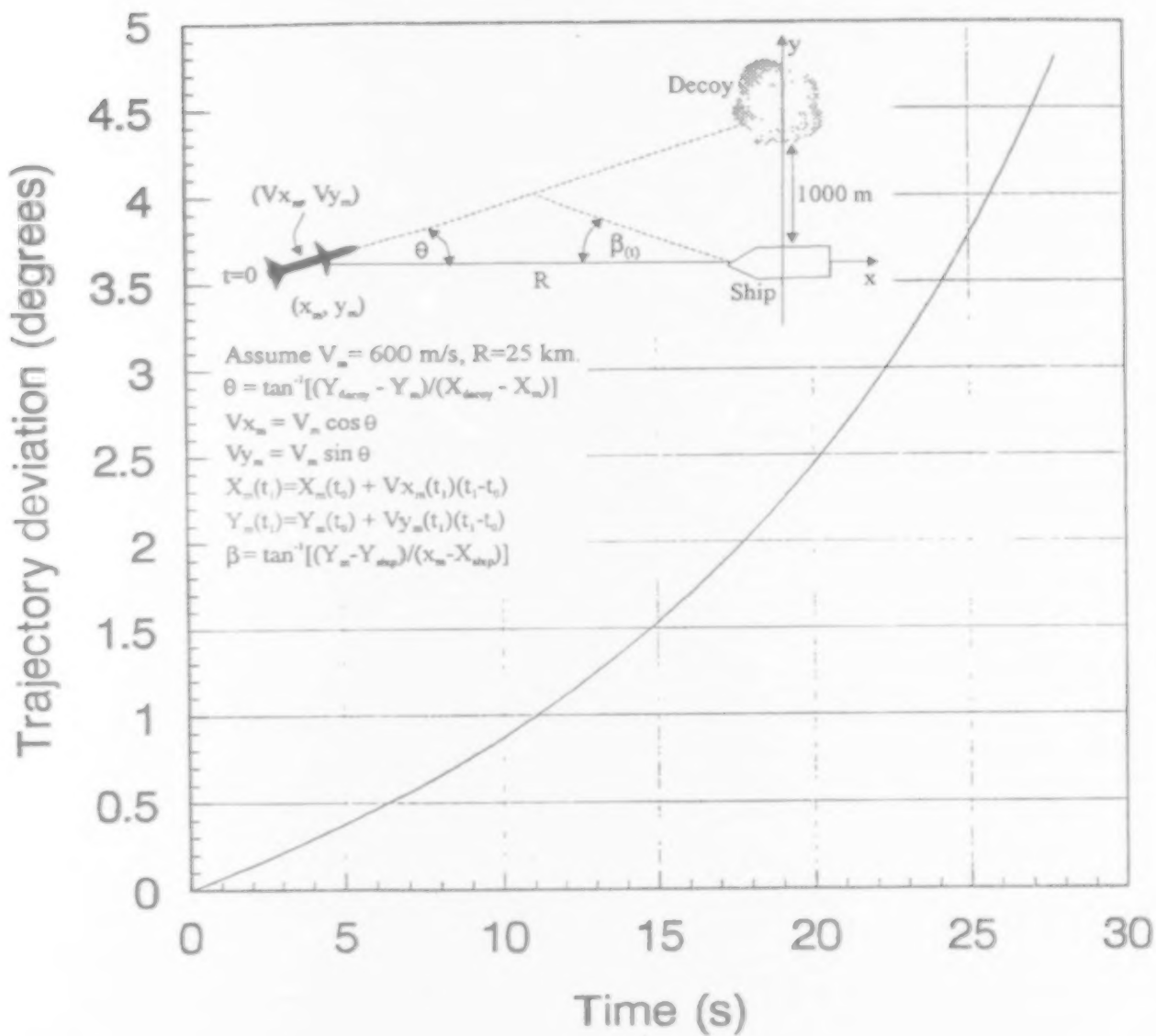


Figure: 5-2 Trajectory Deviation vs Time (Confusion)

5.2 Lock-on Mode

5.2.1 Tracking Disturbed

The goal of this ECM tactic is to produce repeated breaklocks in the seeker's range and angle tracking loops to prevent the threat from achieving proper guidance. The desired ultimate effect is to introduce a miss-distance between the threat and the ship. The use of this tactic, in conjunction with the deployment of decoys, will be addressed in Section 5.2.2. Attempts to disturb the tracking performance of threats are used, quite naturally, against threats that are in track (lock-on) mode against ownship.

The fundamental purpose of this tactic is to use repeated breaklocks to disrupt seeker tracking and cause the threat to ultimately miss the ship. Under a scheme of introducing repeated breaklocks, small pseudo-random heading changes may be introduced in the threat as the seeker continually loses and then regains track of the ship. These might not be sufficient to ensure a significant miss-distance. However, if the introduction of breaklocks is successful over some period of time, the ship will have the capability of manoeuvring out of the path of the missile which is no longer capable of maintaining a steady track. Thus the miss-distance is introduced through the combined effect of seeker track disruption and motion of the ship.

It is also possible that the tactic of disturbing threat seeker tracking will succeed via other mechanisms. If the threat is unable to maintain a steady track, it may fly into the sea. Alternately, under similar circumstances, it may self-destruct as programmed.

A variety of methods are available to accomplish the tactical objective desired. Techniques such as the use of X-pol jamming and the application of SSRM can be used to introduce breaklocks. The effectiveness of such techniques can be augmented through the application of RGPO and the use of NCP. The use of RGPO in conjunction with X-pol, for example, is desirable because RGPO can capture and pulloff the seeker's tracking gate to create a situation in which X-pol need not compete with ship skin return. NCP can facilitate the effectiveness of RGPO in the event that the threat employs leading edge or centroid tracking.

There are a variety of ways in which the effectiveness of the tactic of disturbing threat tracking can be assessed. These include the observation of radar mode changes, antenna deviations (jogs), X-pol / Co-pol variations, and IR signature variations. IR signature variations arise due to the pseudo-random trajectory deviations that are caused by the introduction of repeated breaklocks.

5.2.1.1 Radar Mode Changes

The observation that the threat has undergone a radar mode transition is central to the objective of assessing the effectiveness of a countermeasure whose purpose is to disturb threat tracking. As indicated above, threat tracking is disturbed through the introduction of breaklocks and ESM sensors can be used in order to detect such radar mode transitions on the part of the seeker.

When the threat seeker transitions from one mode (such as track) to another mode (such as re-acquisition or search), a number of specific threat seeker radar parameters may change. These can include changes to antenna scanning behaviour, changes to pulse width, changes to the Pulse Repetition Frequency (PRF), and changes to the carrier frequency.

An ESM system provides the capability of recognizing such changes in seeker behaviour. In particular, the CANEWS ESM system characterizes emitters in terms of scan rate, scan type, pulse width, PRF, and average frequency. This information, along with other signal characteristics, are output to the CCS under the current CPF architecture. The NEWCP can use this information in support of effectiveness assessment.

The ESM system will easily be capable of detecting and characterizing the signals it will receive from threats that are being prosecuted as described above. Attempts to disturb tracking will be made against threats that are in track mode against ownship and are at relatively close range ($< A1 >$ km). Because of the short ranges involved, ESM receiver sensitivity is not an issue.

5.2.1.2 Antenna Deviations (Jogs)

The detection of seeker antenna jogs can support the assessment of the effectiveness of countermeasures whose purpose is to disrupt threat tracking. Certain methods for disturbing the tracking performance of a threat will cause the threat seeker antenna to experience a sudden deviation in angle (jog). For example, the application of course SSRM will produce a jog when the modulation frequency has become equal to the scanning rate of the seeker. Similarly, the use of coarse X-pol with a fast sweep rate will cause the threat antenna to jog due to the resulting short jam dwell time.

Three methods for inferring that a seeker jog has occurred are addressed in Section 3.3 of this report. These include the measurement of seeker antenna reflections (requires active radar illumination of threat), Co-pol / X-Pol measurements, and the measurement of amplitude changes. The following discussion addresses all three of these methods within the context of specific sensors that might support effectiveness assessment using such methods.

Active Radar

One method to detect that a jog has occurred involves illuminating the threat with a radar and measuring the energy reflected from the seeker's antenna. This "jog detection" (JD) radar, used to measure the presence of seeker jogs, will most likely be coherent. As soon as the seeker undergoes a jog, in response to EW attempts to disrupt seeker tracking, a decrease in the amount of JD signal return should be observed.

Coherent radar processing supports the extraction of the relatively weak echo seeker antenna reflection from the clutter background. Typical anti-ship missile speeds will confer a doppler shift of approximately 15 kHz onto the reflected signal. Coherent radar signal processing can

substantially reduce the effect of clutter which will have characteristic doppler shifts well below 15 kHz. A coherent radar also offers pre-detection integration advantages that are vital because of the relatively low RCS of the seeker antenna.

As described in Section 3.3, two fundamentally distinct components are found in the JD reflected signal. First, some of the JD radar energy is absorbed by the seeker and re-radiated. This component is known as the radiation mode response. The second component, known as the structural mode response arises from the reflection of JD radar energy off the antenna, external antenna structures, radomes, and installation cavities.

For both modes of response identified above, the amount of reflected JD radar energy is strongly dependent upon the relative polarization of the JD radar with respect to the seeker antenna. For co-polarization of these two antennas, the radiation mode response is maximized while the structural mode response is minimized. Conversely, if the JD radar antenna is cross-polarized with respect to the seeker antenna, radiation response is minimized and structural response is maximized.

At the time of preparation of this document, no material has been found addressing how the radiation mode response and the structural mode response can be effectively combined in order to provide a characterization of the total amount of JD radar energy return. Accordingly, the remainder of the treatment in this section (active radar) will address the radiation response mode and the structural response mode separately. There is no doubt that a mutual interaction / coupling effect exists between the radiation mode and structural mode responses.

The radiation mode response of the seeker antenna to incident JD radar energy can be characterized in terms of an effective radar cross section, σ_r , which can then be used within the context of the radar range equation to determine whether such radiation mode responses can be detected within the specific context of a countermeasure whose purpose is to disturb the tracking behaviour of the threat seeker. The following expression for σ_r is provided (derivation is presented in Section 3.3.1):

$$\sigma = RCS = |\hat{p}_w \cdot \hat{p}_a|^2 p^2 \frac{G^2 \lambda^2}{4\pi} \cos\theta \left[\frac{J_1(ka \cos(\theta) \sin\theta)}{ka \cos\theta \sin\theta} \right]^2 \quad (1)$$

where,

J_1 = Bessel function of the first kind, order one,

k = wave number,

a = radius of the seeker antenna aperture,

θ = angle between incident signal and seeker antenna boresight.

A calculation based upon the above equation, assuming co-polarized alignment of seeker antenna and JD radar antenna, yields a value of $\sigma_r = 7.5 \text{ m}^2$. This calculation is based upon a circular antenna of radius = 0.2 m and aperture efficiency = 0.6. Note that the range value represents an upper bound on the ranges at which the "disturb tracking" countermeasure will be used against threats described in the threat study.

Consider a radar with a transmit power of 10 kw, a gain of 35 dB, and a wavelength of 0.033 m. Consider also that the range between the threat and the JD radar is <A2> km which represents a typical maximum range at which this technique might be employed for threats of interest. Application of the radar range equation yields a received power level of approximately -86 dBm. Such a signal should be easily detected by the JD receiver chain.

This signal level, representing radiative return energy when the boresights of the seeker and the JD radar are aligned, should be easily detectable at the range of <A3> km.

The structural response mode of the seeker antenna to incident JD radar energy can likewise be characterized in terms of an effective radar cross section, σ_s . This can then be used within the context of the radar range equation to determine whether such radiation mode responses can be detected within the specific context of a countermeasure whose purpose is to disturb the tracking behaviour of the threat. The following equation for σ_s is presented (derivation provided in Section 3.3.1):

$$\sigma = RCS = (1 - |\hat{p}_w \cdot \hat{p}_a|^2) \frac{G^2 \lambda^2}{4\pi} \cos\theta \left[\frac{J_1(ka \cos(\theta) \sin 2\theta)}{ka \cos(\theta) \sin 2\theta} \right]^2 \quad (2)$$

where the various parameters have the same meaning as those provided for equation 1 above.

Similar calculations to those performed for the radiation response indicate that, for target ranges relevant to countermeasures designed to disrupt tracking, the JD radar should have no difficulty detecting the structural response of the threat seeker.

One point of interest relates to the dependence of the radiation and structural responses to variations in Θ . In equation (2) for the structural response, the " $\sin 2\Theta$ " term indicates that the structural response is more sensitive to variations of Θ than the radiation response, where the sensitivity of response to variations of Θ is governed by the $\sin \Theta$ term (equation (1)).

The utility of the antenna reflections method for effectiveness assessment is directly related to the fact that the amount of return energy measured by the JD radar is a reasonably strong function of Θ . The amount of variation in Θ (i.e. the magnitude of the jog) that can be expected when a particular countermeasure is used against a particular threat in a particular situation is not easy to determine. Accordingly, the determination of what changes in energy measured by the JD radar should be taken as representative of a jog is not a trivial problem.

There are a variety of sources of noise that will produce effects at the JD radar that mimic the presence of a jog. For instance, several tenths of a degree of servo-noise can reasonably be expected in seeker behaviour. Furthermore, multipath effects can introduce variations in the return signal energy measured by the JD radar.

Initial investigations into the feasibility of detecting seeker antenna jogs by employing an active radar to measure antenna reflections have yielded promising results. Further investigation / experimentation is needed to confirm that such an approach can be used to determine the effectiveness of countermeasures designed to disturb seeker tracking.

A disadvantage associated with the use of active radars to perform jog detection is that radar emissions may serve to beacon threats and / or broadcast the location of ownship to enemy targeting platforms. Furthermore, active radars cannot be used during EMCON conditions.

ESM

Shipboard ESM systems play a central role in the assessment of ECM effectiveness based on the measurement of jog events. As indicated in Section 3.3 of this report, there are a variety of ways by which a seeker jog can be detected. Two of these three methods use an ESM sensor to perform the necessary measurements. The two methods of interest are the measurement of power fluctuations in received seeker signal and the measurement of fluctuations in the ratio of seeker co-polarized emissions to cross-polarized emissions.

The first of these methods involves measuring the power decay rate of the signal received from a seeker as the antenna jogs in response to a countermeasure. It is to be noted that this method for performing effectiveness assessment is currently implemented in the RAMSES jammer. It can be readily demonstrated an ESM system should easily be capable of detecting the seeker antenna signal for a threat that is subject to countermeasures targeted at disturbing its tracking activities. Note that a reasonable upper limit on target range for such a scenario is $<A_4>$ km, based upon the greatest range at which threats, represented in the threat study, will enter lock-on mode against a ship.

The power level of the signal from the threat seeker is given by:

$$P_{rec} = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \quad (3)$$

where,

P_t = seeker transmit power (40 kw)

G_t = seeker antenna gain (30 dB)

λ = emitter wavelength (3 cm)

G_r = gain of jog detector (JD) antenna (10 dB)

R = radial range between JD antenna and seeker antenna

The values in parentheses represent the values used in the equation to compute received power. For such values, a received power level of approximately -22 dBm is observed. Such a signal is considerably higher than the minimum detectable signals of representative ESM systems.

A more problematic issue concerning the feasibility of this method is whether or not a significant change in this power level can be recognized. Recall that this method is based upon the measurement of the rate of power decay as a function of seeker antenna jog angle. Neglecting the effects of propagation anomalies such as multipath, the power decay rate is a function of the angular rate at which the seeker jogs, the angular magnitude of the deflection, and the shape of the seeker's antenna radiation pattern. With respect to the latter two of these variables, it can be stated that appreciable received signal level changes will only be observed when the magnitude of the antenna deflection is on the order of the half power beamwidth (HPBW) of the threat seeker. Representative calculations characterizing the dependency of received seeker power on such variables are provided in Section 3.3.3 of this report and will not be repeated here. Compared to the other methods for performing jog detection, this method has the disadvantage that relatively large antenna deflections are required in order to ensure jog detection.

Obviously the role of the ESM sensor in this context is to recognize when changes in received seeker power can be attributed to a seeker jog and not to other factors. As described in Section 3.3.3, the measured power decay rate associated with a seeker jog is not constant over time. Accordingly, systems such as RAMSES do not attempt to measure instantaneous power decay rates; instead the system attempts to characterize jogs by measuring the rate of received power decay over a specific time interval. For RAMSES, a jog is declared if threat signal decreases at a rate $> <A6>$ dB/s over an interval of 0.25 seconds.

It is simple to demonstrate the dynamic range of the ESM receiver should not limit the measurement of antenna jogs as described above. A representative dynamic range for a logarithmic receiver is 60 dB, while an AGC type receiver typically provides a dynamic range of 30 dB.

Finally, the multipath effect introduces an element of ambiguity concerning this method for jog detection. In particular, multipath reflections produce fluctuations on the amount of seeker power incident upon an ESM receiver. Such variations will occur in the absence of real seeker antenna jogs and yet may produce effects that mimic such jogs. To address this problem, vertical antenna arrays have been proposed as one design solution. The role of a vertical array of ESM receive antennas in reducing the ambiguity introduced by the multipath effect is described in Section 3.3.3.2 of this report.

ESM receivers can also be used to recognize seeker jogs by exploiting the fact that the ratio of emitter co-polar emissions to cross-polar emissions changes as an observer moves off in angle from seeker boresight. As described in Section 3.3.2 of this report, the ratio of co-polarized seeker emissions to cross-polarized emissions is a strong function of observation angle. In particular, this ratio can be significantly more sensitive to variations in the observation angle than measurements of co-polar emissions will be.

A critical issue concerning the feasibility of this method for detecting jogs is the question of whether the seeker's cross-polar signal will be detectable by the shipborne ESM receiver. As described in detail in Section 3.3.2, the seeker's cross-polar signal may be much weaker than the co-polar signal. This is particularly true when the antenna of the ESM system being used to perform jog detection lies on (or very near to) the seeker's line of sight. Under such conditions, the cross-polar signal may be as much as 40 dB below the co-polar signal. The jog detector system must have sufficient sensitivity to detect the residual cross-polar signal near the boresight of the missile antenna.

The amount of seeker power incident upon the ESM system used for detection can be estimated through an application of the one-way radar range equation:

$$P_r = \frac{\lambda^2 P_t G_{\alpha} G_{\sigma}}{(4\pi R)^2} \quad (4)$$

where,

P_r = power received at jog detector antenna

λ = radar wavelength

P_t = transmitter power of missile

G_{α} = gain of missile antenna

G_{σ} = gain of jog detector antenna

R = range between the jammer and radar

Note that the values provided in parentheses for each parameter are those used in the computation of the amount of seeker power delivered to the ESM receiver chain. Also note that the value of $R = <A8>$ km is an estimate largest threat - ship range relevant to countermeasures whose

purpose is to disturb threat tracking. Evaluating this equation for the values indicated, the co-polar signal received at the jog detector (assuming perfect polarization matching between missile and jog detector antennas) is approximately -16 dBm. If the cross-polar signal near boresight of the seeker antenna is 40 dB below the co-polar signal, the minimum detectable signal of the ESM system must be less than or equal to about -56 dBm in order for this method of jog detection to be feasible.

Once more, multipath effects can introduce an element of ambiguity into this method for performing effectiveness assessment. Low grazing angle co-polar scatter is expected to differ from low angle cross-polar scatter. A technique is required to discriminate between multipath effects and true seeker jogs in terms of generating fluctuations in the ratio of co-polar power to cross-polar power. One option in this regard is to employ a vertically aligned set of antennas (as described immediately above for the jog detection method based on amplitude fluctuations). Another possibility is to correlate apparent seeker jogs with specific ECM activities in order to filter out the effects of multipath.

5.2.2 Decoy Seduction

The goal of this ECM tactic is to cause the threat's seeker to be seduced away from the ship onto a decoy. A decoy seduction tactic involves no attempt to change the fundamental mode of operation of the seeker (e.g. no attempt to force a seeker into acquisition or search modes). Decoy seduction is targeted at threats that are in track (lock-on) mode against ownship. It is important that the decoy be initially deployed relatively near ownship to ensure that the decoy is within the seeker's tracking cell. The decoy then serves as a competitive target to ownship. If the tactic is successful, seeker track will be transferred to the decoy and the threat will subsequently navigate towards the decoy and hence not intercept ownship.

A variety of decoys, both active and passive, can be used to accomplish the seduction objective. Decoys can be electronic artifacts, such as the pulse associated with a Range Gate Pull Off (RGPO) countermeasure or the signal produced by an Active Offboard Decoy (AOD). Furthermore, decoys can be used in combination in order to achieve the seduction objective: RGPO can be used in conjunction with chaff, for example. Decoys that can be used to accomplish seduction include seduction chaff, rubber ducks, AODs, IR flares, and the use of RGPO and Noise Cover Pulse (NCP).

As alluded to above, the ultimate objective of a decoy seduction tactic is to cause the threat to change its trajectory away from ownship and towards the decoy. However, additional phenomena with effectiveness assessment value may be observed. These include chaff reflections and antenna jogs.

5.2.2.1 Trajectory Change

The observation that the threat has altered its trajectory in order to pursue the seduction decoy is of central importance to assessing effectiveness of the decoy seduction tactic. Trajectory changes may be directly measured using ship sensors (e.g. radar) to track the target. Alternately, trajectory deviations may be inferred from measurements of doppler shifts and IR profile variations. Doppler shifts may be observed when a threat employing an active radar changes direction to pursue a decoy target; the doppler shift in the threat's emitted signal is caused by a change in threat radial velocity as measured by ownship. Similarly, as a threat changes direction in response to successful decoy seduction, the IR signature of the threat exhaust plume, as measured by ownship, will change as indicated in Section 3.2.3. Both direct and indirect methods for determining that a trajectory change has taken place can be used in support of effectiveness assessment.

Direct measurement of a threat trajectory deviation involves using sensor measurements to determine that a threat has changed its heading. A threat that is radial inbound with respect to ownship will subtend a particular azimuth angle as measured from the ship. If a decoy seduction countermeasure is successful, this angle will change with time as the threat develops a crossing velocity component (i.e. changes its heading). At some point in time, the angular motion of the threat should, in principle, be subject to observation by ship sensors.

A knowledge of the position of the relevant decoy can assist when using trajectory change data to perform effectiveness assessment. More specifically, the change in trajectory of the threat should be consistent with the assumption that the threat is indeed pursuing the decoy. Trajectory deviations that are not consistent with decoy position are more likely to represent manoeuvres on the part of the threat. The degree of confidence associated with the positional characterization of the decoy may be highly variable.

As indicated above, a trajectory deviation on the part of the threat can be inferred as the result of measurements of doppler shifts in the emissions of threats. Because the AS-6 ARM threat does not radiate, this technique cannot contribute to an assessment of the effectiveness of countermeasures undertaken against such threats. It is also to be noted that the doppler shift method characterizes *changes* in threat radial velocity and does not provide a characterization of the radial velocity itself.

In principle IR signature measurements and apparent missile length changes (as measured by a radar) could also be used to infer a change in threat direction. As the threat alters its trajectory in pursuit of a seduction decoy its IR energy output, as measured by the ship, may change as (for example) more of the exhaust plume is exposed. Similarly, as the threat changes direction from a purely radial in-bound trajectory, the depth of the target, as measured by a ship-borne radar, will be reduced. However, as described in Sections 3.2.3 and 3.2.4 of this report, preliminary study and analysis indicates that the measurement of such effects is beyond the capability of existing sensor systems.

Possible ambiguities associated with the measurement of a change in missile trajectory include the possibility that a change in threat heading might be attributable to a pre-programmed manoeuvre.

The following material describes the roles that various candidate sensors can perform in order to support the measurement of threat trajectory changes that are consistent with the successful implementation of a decoy seduction countermeasure.

Active Radar

Active radars can be employed to directly measure target position and hence provide indication of trajectory deviations. For a variety of reasons, some more obvious than others, there will always be a temporal overhead associated with the recognition of a trajectory deviation. Threats against whom a decoy seduction tactic is being employed are generally in their final phase of attack and will be quite close to the ship (< <A9> km). Specified threats can take as little as <A10> seconds from entry into lock-on to intercept of their target. Accordingly, rapid determination of decoy effectiveness is important in order for the assessment to have any value at all in terms of allowing for the implementation of some further defensive options.

Some active radars, such as the SPS-49 and the Sea Giraffe scan the hemisphere for targets and will only interrogate a particular target on every antenna rotation. Suppose, for example that a certain threat underwent a dramatic trajectory deviation a fraction of a second after it has been illuminated by such a radar. No matter how accurate the radar, it will be impossible to measure a trajectory change prior to the next illumination of the threat. For the SPS-49, the rotation period can be as long as <A11> seconds while the rotation period of the Sea-Giraffe radar can be as long as <A12> seconds.

By contrast, the STIR fire control radar is a dedicated tracking radar and, for all intents and purposes, provides target information on a continuous basis. Similarly, the phased array antenna technology associated with the MFR allows this radar to schedule target updates, or dwells, as needed.

Figure 5-3 provides an indication of how the angular position of a threat varies with time when a seduction decoy is successfully deployed in the vicinity of ownship. More specifically, the dependant variable plotted (against time) represents the angle difference, as measured from ownship, between the bearing of a deceived threat and the bearing of a threat which is not deceived and maintains a radial inbound trajectory. Each of the two curves plotted represents a different threat scenario; for reasons of classification the threat trajectories represented are based upon representative data, hence the curves are identified as "Threat A" and "Threat B".

Each curve represents the trajectory deviation of the threat to the deployment of seduction chaff. It is assumed that chaff is deployed approximately 100 metres from ownship and that the combined effect of the wind and ship motion are such as to cause the chaff cloud to close on the

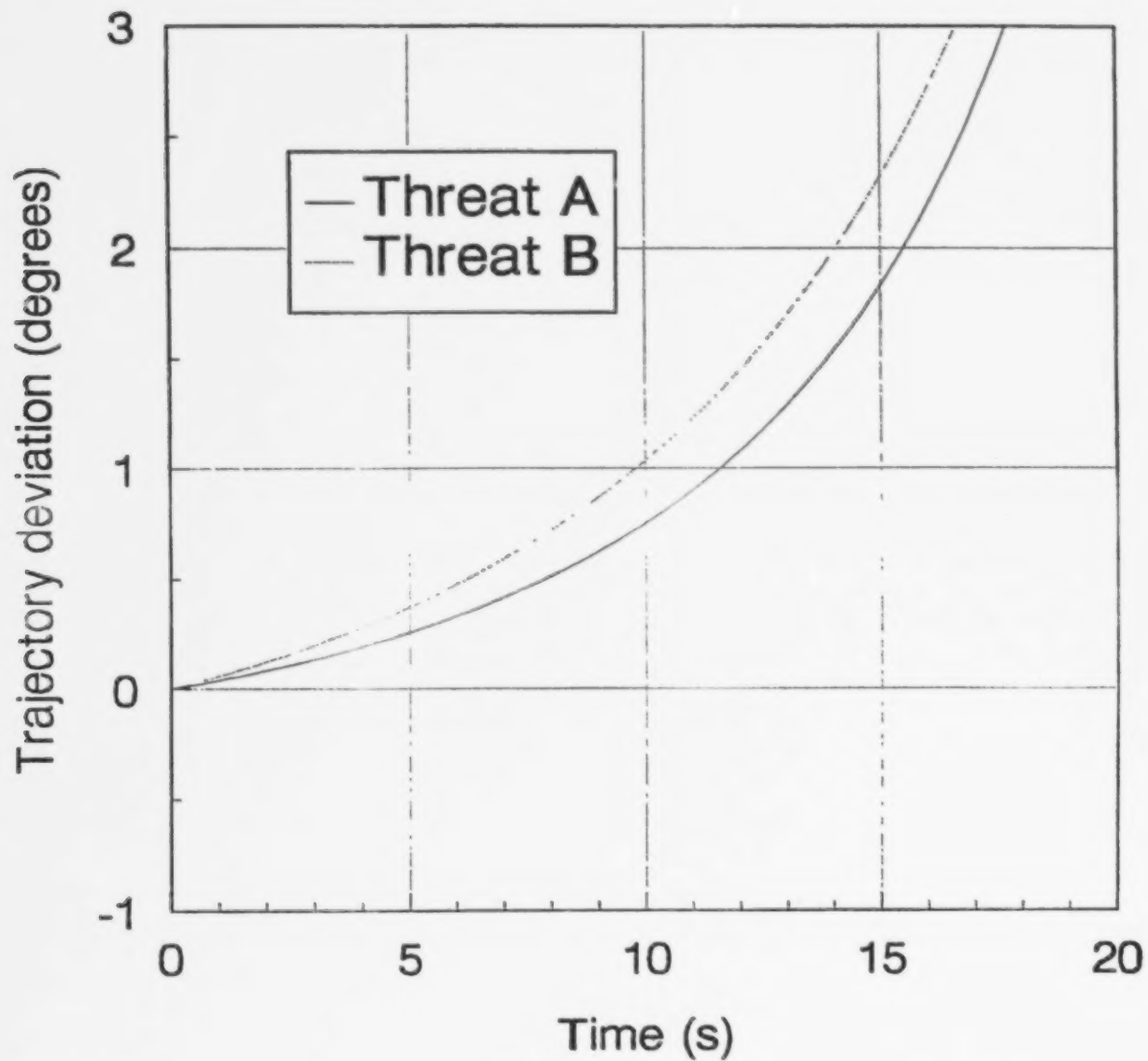


Figure 5-3 Trajectory Deviations vs Time (Seduction)

ship and pass immediately over the ship and then for the decoy and the ship to separate. It is assumed that the threat will transfer lockon to the decoy as soon as it appears. It should be underscored that although two different angle deviation profiles are provided, representing different threat types, the exact same decoy is deployed against each threat. Ship motion and wind are the same for both cases as well.

These curves allow a determination of the time required to identify a threat deviation for a particular sensor. For example, consider a sensor with an angular accuracy of 1° . For Threat A, more than 12 seconds are required from initial detection to the moment at which the induced angular trajectory change exceeds the accuracy of the sensor. The corresponding time value for Threat B is approximately 11 seconds.

The angular accuracies of various CPF active radar sensors are provided as follows:

- | | | |
|----|-------------|-----------------------------|
| a. | SPS-49 | $\langle A13 \rangle^\circ$ |
| b. | Sea Giraffe | $\langle A14 \rangle^\circ$ |
| c. | STIR | $\langle A15 \rangle^\circ$ |
| d. | MFR | $\langle A16 \rangle^\circ$ |

One can use these values in conjunction with the trajectories provided in Figure 5-3 in order to determine the time required for a particular sensor to "recognize" that a trajectory deviation has indeed taken place. Once more, it has been assumed that a trajectory deviation is recognized once the trajectory deviation exceeds the sensor's angular accuracy. Because of the relatively short ranges ($\langle A17 \rangle$ km) of threats subject to decoy seduction countermeasures, the issue of target detectability by ship active radars is not considered to be problematic, subject to possible effects of multipath interference. For a discussion of the effects of clutter and multipath on active radar measurements, please refer to Section 4.2.1.1 of this report.

A disadvantage associated with the use of active radars to perform effectiveness assessment is that radar emissions may serve to beacon threats and / or broadcast the location of ownship to enemy targeting platforms. Furthermore, active radars cannot be used during EMCON conditions.

Electronic Support Measures (ESM)

An ESM can system can support the recognition of threat trajectory deviations in two ways. First, its capability to measure target azimuth can, in principle, be used to directly measure changes in target heading (as described above for active radars). Second, the capability of an ESM to characterize the frequency of threat emissions can be used to indirectly infer that a change in threat trajectory has taken place. Of course, the ESM sensor can only contribute to effectiveness assessment activities if the threat is employing an active radar seeker.

Figure 5-4 provides a diagrammatic representation of an EW engagement based upon the tactic of decoy seduction. This scenario illustrates an engagement involving a threat representative of

those described in Sections 5.1, 5.2, and 5.3 of the threat study]. Seduction chaff is assumed to be deployed at a range of 300 m from ownship and is assumed to move with a constant velocity. The purpose for the provision of this engagement scenario to provide an appropriate context for a discussion of ESM trajectory measurement and doppler shift measurement capabilities. Note that for purposes of classification, some numbers have been omitted from the graph.

It has been assumed that the threat is successfully seduced by the decoy almost immediately after it has locked onto the ship. The diagram represents the geometrical conditions that apply at this time. It is further assumed that the threat, which had been heading directly for the ship, instantaneously alters its trajectory to head for the decoy.

The CANEWS ESM system employed on CPF does not provide particularly effective angular measurement accuracy to support effectiveness assessment though direct measurement of target angular position. If it is assumed that the threat begins to head directly for the decoy immediately upon entry to lock-on mode (i.e. at a range of <A18> km), the change in angular position of the threat does not exceed <A19>° until it is <A20> km from the ship.

The effectiveness of the method of using doppler shift measurements to infer a change in trajectory depends upon the geometry of the engagement as well as upon the ability of the sensor to measure small changes in target emission frequency. More specifically, a change in threat heading of Θ° , produced by decoy seduction, will produce the following doppler shift:

$$f_d = - \frac{V_t(1 - \cos\theta)}{\lambda} \quad (5)$$

where

V_t = radial velocity of threat prior to EW deployment

θ = change in threat heading

λ = wavelength of threat emissions

One parameter of interest is the target-ship range at which a change of threat heading of Θ° can be recognized. This range depends upon the accuracy with which the ESM system can characterize emission frequency. The greater the accuracy of the ESM system, the further the range at which the change in heading can be recognized.

V_{THREAT} (SS-N-22) = m/s

V_{THREAT} (SS-N-19) = m/s

V_{THREAT} (HARPOON) = m/s

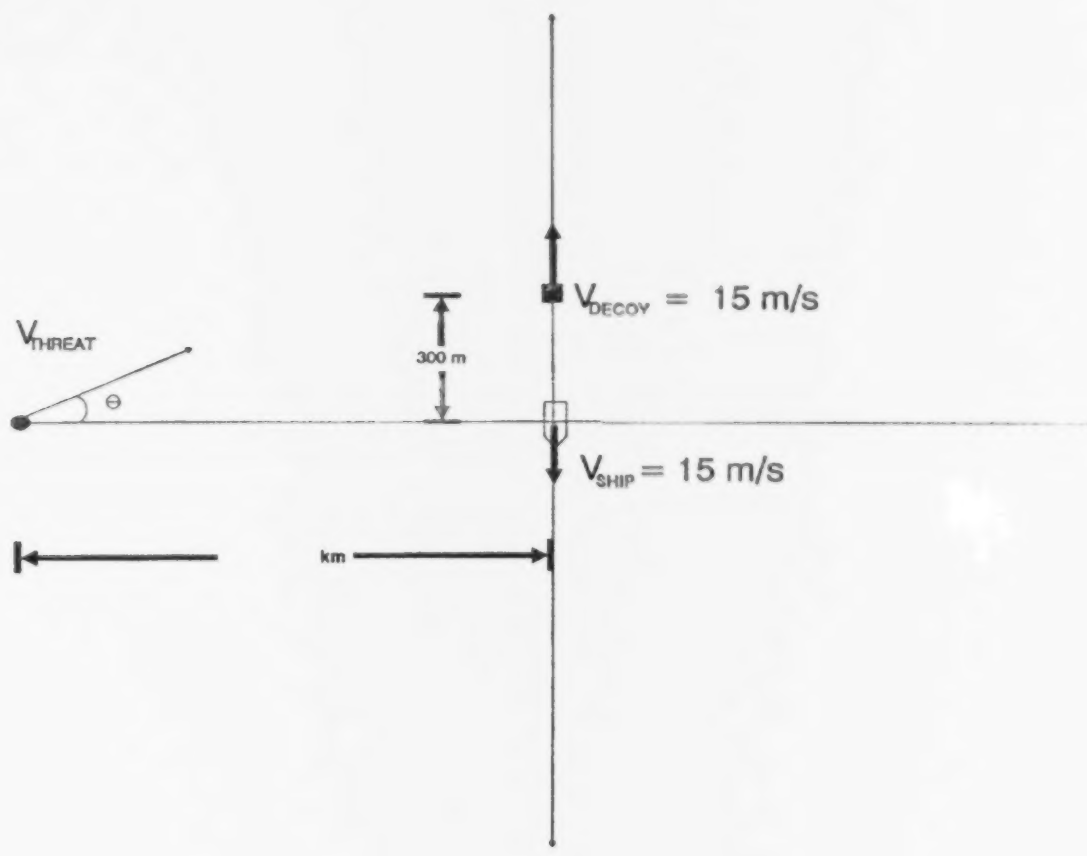


Figure 5-4 Engagement Geometry - Decoy Seduction

Consider an ESM system with the capability of measuring doppler shifts to an accuracy of 10 Hz. Table 5-1 indicates the minimum threat heading change (Θ) that can be detected for each of the three representative threats. Recall that Θ is a function of the threat speed which differs for the three missiles even though the geometry of engagement is roughly the same. It is assumed that the wavelength of the threat's emitted signal = 0.03 m. The values of provided in the table are derived by solving equation (1) for Θ .

TABLE 5-1 Maximum detected heading change.

THREAT TYPE	Θ
HARPOON	<A21>
SS-N-22	<A22>
SS-N-19	<A23>

Straightforward geometrical reasoning can be used to determine the maximum threat-ship range at which a threat change in heading of Θ° can be recognized by ownship. Let this range be denoted by R_{ESM} and its value is given by the following expression:

$$R_{ESM} = d / \tan(\Theta) \quad (6)$$

where d is the separation of the decoy from ownship. Table 5-2 provides the values of R_{ESM} for each of the three representative threats within the context of the engagement scenario represented in Figure 5-4. Once more, it is that assumed the wavelength of the threat's emitted signal is .03 m.

TABLE 5-2 Maximum threat range to measure Θ .

THREAT TYPE	R_{ESM}
HARPOON	<A24>
SS-N-22	<A25>
SS-N-19	<A26>

The ability of an ESM system such as CANEWS to accurately measure doppler frequencies of interest is of course critical to the effectiveness of this method. The calculations provided above are based upon an ESM system that is capable of measuring doppler shifts on the order of 10 Hz.

The technical challenges to be overcome in providing such frequency measurement accuracy are

discussed in Section 3.2.2.10 of this report. The CANEWS ESM system does not provide the required frequency measurement accuracy to support the requirement.

As indicated in Section 3.2.2 of this report, the Cramer-Rao bound can be used to characterize the best possible accuracy for target frequency measurement in the presence of noise. More specifically, it is the minimum variance or mean-square error associated with a frequency measurement. The Cramer-Rao bound is a function of the Signal to Noise Ratio (SNR), the number of signal samples (N), and the sampling rate ($f_s = 1/T_s$) and is given as follows:

$$\sigma_{\omega}^2 \geq 6f_s^2 / [(SNR) N (N^2 - 1)] \quad (7)$$

where ω is expressed in units of radians.

As alluded to above, an ESM sensor cannot support effectiveness assessment if the threat is not radiating.

Precision Electronic Support Measures (PESM)

A precision ESM system with a High Accuracy Direction Finder (HADF) can be employed to support the measurement of trajectory deviations within the context of the deployment of a decoy seduction countermeasure. The superior angle measurement accuracy associated with such a sensor (approximately 0.1°) makes it suitable to direct measurement of trajectory deviations.

Figure 5-3 provides a diagrammatic representation of an EW engagement based upon the tactic of decoy seduction. Important details about how to interpret this diagram are provided in the above section describing active radars.

Based upon an analysis of the geometry of the engagement, it can be demonstrated that the trajectory deviation induced by the decoy seduction effect will be recognized immediately after the threat actually changes trajectory. The PESM thus provides strong effectiveness assessment support in terms of direct measurement of the trajectory deviations associated with a successful decoy seduction deployment.

As is the case for the ESM system, the PESM system cannot contribute to effectiveness assessment if the threat is not radiating.

IR Tracker

An IR sensor, with its capability to accurately characterize target angular position (azimuth and elevation) can play a role in the direct measurement of trajectory changes induced by decoy seduction countermeasures. For this particular role, a dedicated IR tracker provides superior performance than an Infra-Red Search and Track (IRST) system. The IR tracker is dedicated to

a single target and provides an uninterrupted stream of measurements whereas anIRST system scans the hemisphere at a relatively slow rate (typically 3 s/rev) and requires that multiple contacts be observed before the creation of a track.

Based upon available information, the angular accuracy associated withIRST measurements is approximately 0.1° while the angular accuracy associated with an integrated IR tracker can be on the order of 0.01° .

Figure 5-3 provides a diagrammatic representation of an EW engagement based upon the tactic of decoy seduction. Important details about how to interpret this diagram are provided in the above section describing active radars.

Based upon an analysis of the geometry of the engagement, it can be demonstrated that the trajectory deviation induced by the decoy seduction effect will be recognized immediately after the threat actually changes trajectory. This is based upon an assumed angular accuracy of 0.1° . The IR sensor thus provides strong effectiveness assessment support in terms of direct measurement of the trajectory deviations associated with a successful decoy seduction deployment.

Fundamental disadvantages associated with IR sensors include their limited range (approximately 20 km) and their degraded performance in the presence of fog or precipitation.

As indicated in Section 3.2.3 of this report, it is not anticipated that IR sensors will be capable of supporting an inference of threat trajectory change through the measurement of changes to IR emissions as the threat changes its heading.

5.2.2.2 Chaff Reflections

The following material describes the roles that ESM sensors can perform in order to support the measurement of chaff reflections that are consistent with the successful implementation of a decoy seduction countermeasure.

If a threat, employing active radar, has been successfully prosecuted by the use of seduction chaff, threat seeker energy will be directed towards the chaff which may then scatter some of this energy towards the ship where it can, in principle, be measured. If such chaff reflections are indeed observed, support is provided to the hypothesis that the threat has been successfully seduced by the chaff.

An ESM system will be the principal sensor used to measure such chaff reflections. An HADF system associated with a PESM system may provide additional effectiveness assessment information. The high angular accuracy of such a system may support a determination that the apparent source of microwave energy is an extended body. A chaff cloud deployed in the

vicinity of the ship may subtend a substantial angle as observed from ownship. Accordingly, the HADF system may be capable of recognizing that microwave energy is arriving from a window of angles. Such an observation is consistent with reflections from chaff, but not with direct line of sight seeker emissions.

The following bi-static radar range equation [Ref = Skolnik] provides a method for estimating the amount of seeker energy, reflected from chaff, that will be measured by an ownship ESM system:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma_c}{(4\pi)^3 R_{sc}^2 R_{mc}^2 L_{mc}(t) L_{sc}(r)} \quad (8)$$

- P_t = transmit power (100 kw)
- G_t = transmit antenna gain (1000)
- G_r = receive antenna gain (10)
- λ = wavelength (0.03 m)
- σ_c = bi-static RCS
- R_{sc} = range between ship and chaff
- R_{mc} = range between missile and chaff
- $L_{mc}(t)$ = propagation loss for R_{mc} (1)
- $L_{sc}(r)$ = propagation loss for R_{sc} (1)

Values provided in parentheses are considered to be nominal. The derivation of the bi-static radar cross section, σ_c , is complex and is addressed in detail in Section 3.4 of this report. Nevertheless, several values of σ_c can be postulated and the associated levels of received power calculated. More specifically, we are interested in computing received power dependence upon threat - chaff range as a number of variables associated with equation (4) are varied. Free variables of interest include:

- Transmit power;
- Range between ship and chaff; and
- Chaff bi-static radar cross-section.

Transmit power is of interest because the seeker output power is different for different threats as specified in the threat study. In addition, we are interested in examining the dependence of received power upon the range from ownship at which chaff is deployed. Finally, because of the difficulty in providing a single value for chaff bi-static radar cross section, a number of representative values will be used.

Figures 5-5 through 5-8 provide a graphical representation of the dependence of received power upon threat - chaff range as the free variables identified above assume a variety of values. The values used for each of these variables are indicated on the graphs themselves. The situations

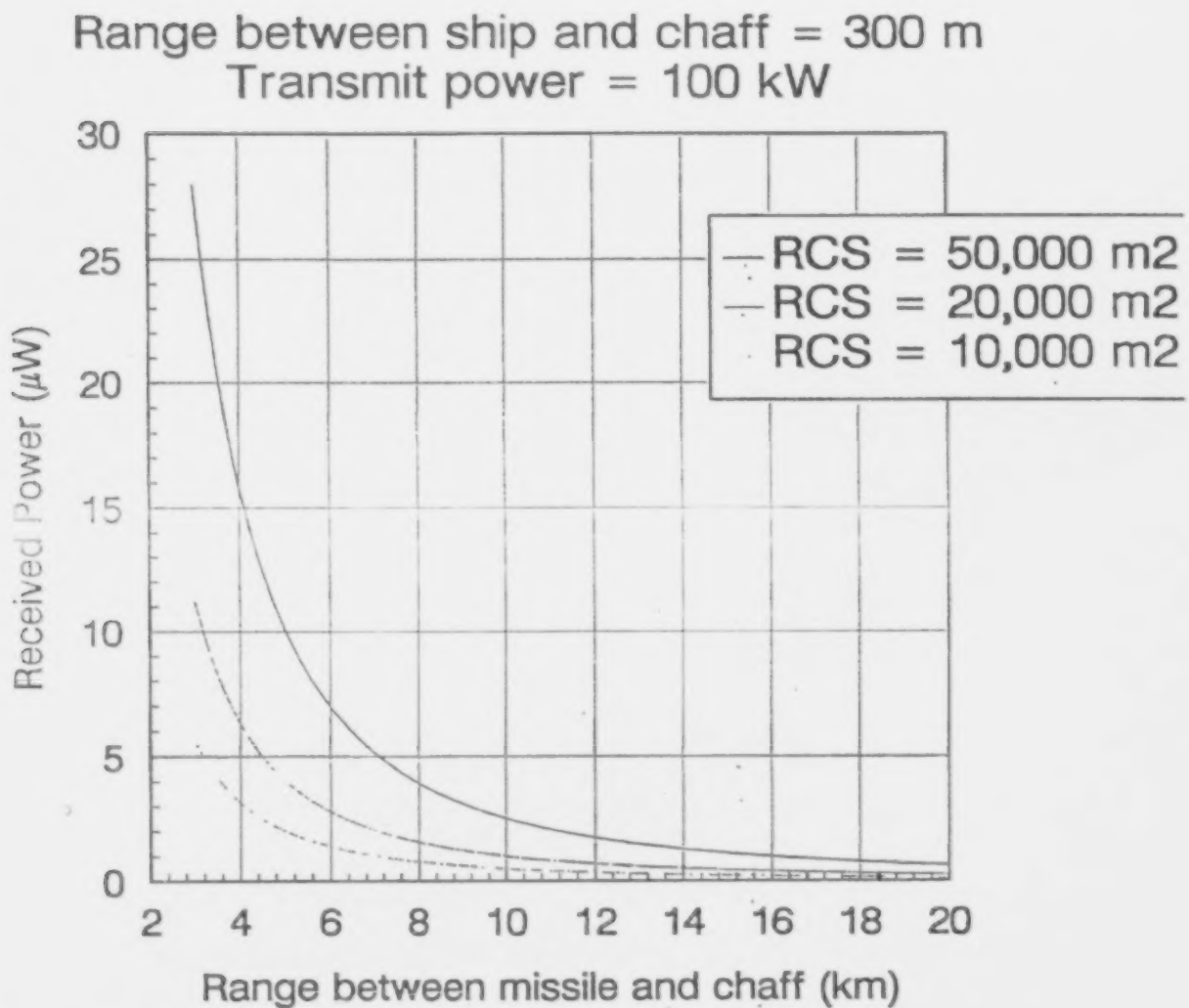


Figure: 5-5 Received Power vs Range (Chaff Reflections)

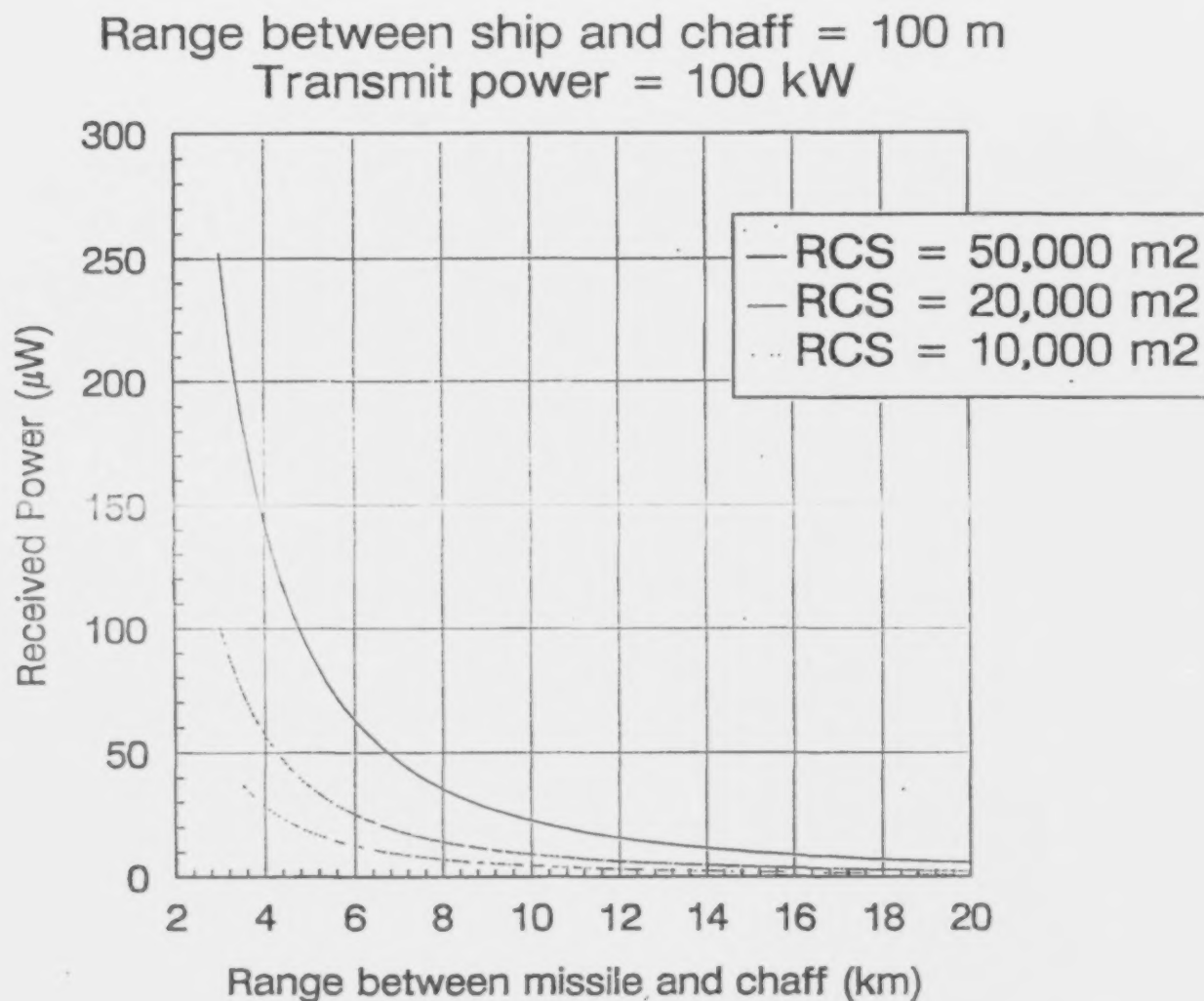


Figure: 5-6 Received Power vs Range (Chaff Reflections)

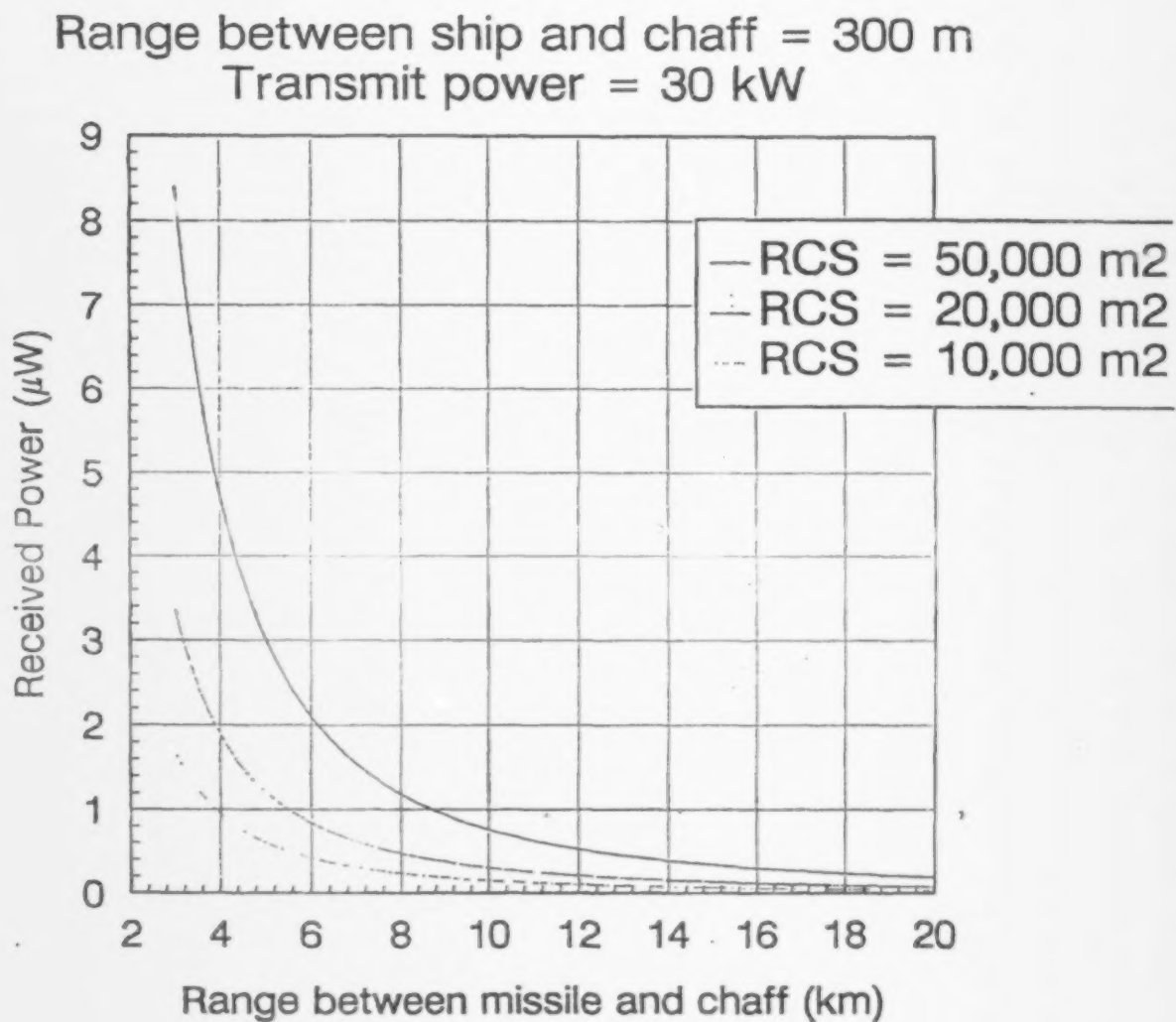


Figure: 5-7 Received Power vs Range (Chaff Reflections)

Range between ship and chaff = 100 m
Transmit power = 30 kW

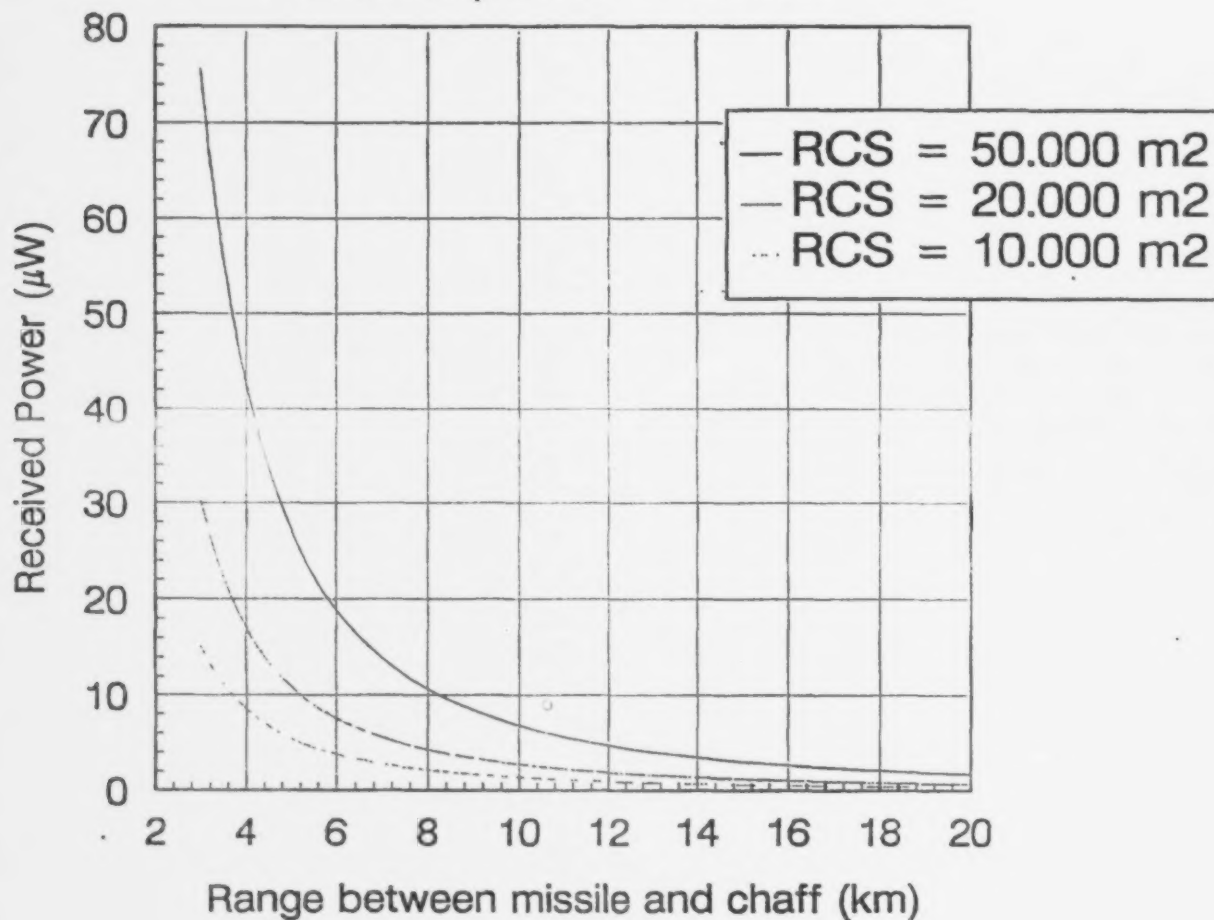


Figure: 5-8 Received Power vs Range (Chaff R5-reflections)

described by these graphs are only intended to be representative and of course do not address all possible engagement scenarios. Threat-chaff ranges are limited to those that are meaningful within the context of a decoy seduction deployment (i.e. $< A_{27} >$ km).

5.2.3 Tracking Disturbed / False Target Acquisition

The goal of this ECM tactic is to produce repeated breaklocks in the seeker's range and angle tracking loops and then have the threat acquire a decoy target. As such, this tactic is a variant of the tactic addressed in Section 5.2.2. Once a breaklock has been induced in the threat, it will enter a reacquisition mode or search mode. In such modes, the deployed decoy becomes a potential target for the threat. Ideally, the timing and geometry of the decoy deployment is such as to optimize the likelihood that the threat will, after breaklock, acquire the decoy as compared to the ship.

As is the case for the tactic described in Section 5.2.2, the desired ultimate effect is to introduce a miss-distance between the threat and the ship. The presence of a decoy target should increase the overall probability that the ship will not be reacquired. Attempts to disturb the tracking performance of threats and subsequently cause them to acquire an alternate target are used against threats that are in track (lock-on) mode against ownship.

A variety of methods are available to accomplish the tactical objective desired. The introduction of seeker breaklocks is generally accomplished in the same manner as described in Section 5.2.2. Typically, the application of such jamming techniques as cross-pol and SSRM are preceded by the use of NCP, RGPO, and a Hold-Out (HO) pulse. The use of RGPO is desirable because RGPO can capture and pulloff the seeker's tracking gate to create a situation in which cross-pol or SSRM need not compete with ship skin return. NCP can facilitate the effectiveness of RGPO in the event that the threat employs leading edge or centroid tracking. The HO pulse is applied to keep the threat from reacquiring the ship during the transition between the use of RGPO and the application of the specific jamming method used to introduce breaklocks (e.g. cross-pol, SSRM).

The decoy component of the tactic can be accomplished through the deployment of such alternate targets as chaff, rubber ducks, or an active off-board decoy (AOD).

The methods for assessing the effectiveness of the tactic described in this section are essentially the same as those already addressed in Sections 5.2.1. and 5.2.2 of this report. This is because the tactic under consideration represents a combination of the tactic of disturbing tracking and the tactic of decoy seduction. As indicated above, efforts to disturb tracking are used to force the seeker into a reacquisition or search mode where it can subsequently acquire the decoy.

Assessing the effectiveness of attempts to implement such a combined tactic is accomplished by an assessment of the effectiveness of the disrupt tracking component followed by an assessment of the effectiveness of the decoy component. Thus, effectiveness assessment for this the

combined tactic is essentially a two step process. First, the effectiveness of the disturb tracking component is assessed by the measurement of radar mode changes and antenna jogs. Second, the effectiveness of the decoy component is assessed by measuring changes in trajectory and, if applicable, chaff reflections.

These particular methods for effectiveness assessment and the role that various sensors play in providing the necessary supporting measurements have already been discussed in Sections 5.2.1 and 5.2.2. Accordingly, this material will not be reproduced here. Several issues, specifically relevant to the combined tactic of tracking disruption and decoy deployment will however be addressed.

As indicated above, effectiveness assessment for this combined tactic can be viewed as a two step process. First, the effectiveness of the disturb tracking component is assessed and then the effectiveness of the decoy deployment is assessed. This two step approach gives rise to a question of timing. More specifically, will the time overhead associated with assessing the effectiveness of the disturb tracking component be so large that insufficient time remains to assess the effectiveness of the of the decoy component? Assessing the effectiveness of decoy deployments is addressed in Section 5.2.2, above.

It certainly does not appear that this timing issue will be a problem. Methods for assessing the effectiveness of tactics that disturb threat tracking require very little time. Recognition of seeker jog, whether accomplished via a jog detection radar (seeker antenna reflections) or an ESM system (measurement of amplitude changes, measurement of co-polar to cross-polar emissions), will require relatively little time. In addition, the recognition of seeker radar state transitions should be almost instantaneous. For these reasons there should be as much time available to assess the effectiveness of the decoy component of the combined tactic as there is to assess the effectiveness of a decoy seduction countermeasure.

In fact, it can be argued that assessing the effectiveness of the decoy component of the combined tactic will require less time than an assessment of the effectiveness of a decoy deployed for purely seduction purposes (Section 5.2.2). This is due to the fact that a decoy deployed within the context of the combined tactic will not generally need to be as close to the ship as is the case in a decoy seduction deployment. In a decoy seduction deployment, the decoy needs to be close enough to the ship to ensure that it will be within the seeker's tracking gate. This requirement is somewhat relaxed within the context of the combined tactic because the introduction of breaklocks into the seeker will cause it to transition to a reacquisition or search mode. The decoy then need only be within the volume of space that will be interrogated by the seeker in such modes. If the decoy is deployed relatively far from the ship (as compared to the decoy seduction case), then any trajectory changes on the part of the threat, attributable to the effect of the decoy, will be more pronounced than in the case of a decoy seduction deployment. Because such trajectory changes may be more significant (i.e. larger angular change in threat heading), they may be more rapidly recognized by ship sensors such as radar and IRST.

6.0 AMEP CONCEPTS

The Advanced Modular ESM Processor (AMEP) can contribute in two ways to the effectiveness assessment (EA) capabilities of the Electronic Warfare Control Processor (EWCP). These are: 1) Techniques for developing information of types already generated or expected to be generated by the AMEP system, and 2) Design and implementation concepts which can be re-used in the implementation of new processing capabilities in the EWCP. These are dealt with separately in the subsections which follow, and are related to EA requirements they may help to fulfil.

6.1 Information Generated by the AMEP

The EW Support Measures (ESM) system is capable of providing some support for Effectiveness Assessment (EA). These capabilities are limited by certain design factors. In particular, an ESM set's very rough (if any) approximation of range, and its rather modest bearing accuracy make it inappropriate for provision of detailed information to assist with missile dynamic behaviour analysis. On the other hand, the ESM excels at the analysis of the structure of pulse trains. This makes it a natural contributor of information on mode changes, on the presence and absence of particular emitters in the environment over time periods of seconds to minutes, and on scan types and their changes. These capabilities of AMEP are discussed and related to the EA problem in EWCP in the sub-sections which follow.

6.1.1 Mode Change Detection

The AMEP has been designed to provide detection of mode changes in Radio Frequency behaviour, Pulse Repetition Interval (PRI) pattern, and Scan pattern. The algorithms will not be examined in detail here. However, it should be noted that they make use of techniques described in the AMEP Design and Implementation Concepts section below.

These capabilities are directly applicable in EWCP in the following areas:

Mode Change	a) EA for search radar denial. b) EA for seeker acquisition denial. c) EA for seeker false target acquisition (here absence of mode change is the significant feature). d) EA for seeker lock-on disturb tracking. e) EA for seeker lock-on to false target. f) EA for seeker lock-on seduction to a decoy (here the absence of mode change is the significant feature).
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6.2 Continuity of Threats in the Environment

The AMEP, at the level of the Tactical Situation Analyst, is capable of making sophisticated hypotheses to correlate emitter tracks to platforms, and to other emitter tracks of possibly contrasting modes. In this way it is able to form a picture of the environment wherein various appearances of a single emitter are properly grouped. If, for example, an emitter changes modes, the system will not merely allow the first track to be removed due to inactivity. Rather, it will associate this track with that caused by the new mode of the emitter. The presence of this form of processing lends additional confidence to the judgement that an emitter has in fact disappeared from the environment, and is useful to EWCP in the following area:

Threat persistence	a) EA for Search radar targeting, onboard generation of false target. In this case, the missile is expected to self-destruct or flyout of range, and a strong judgement that it is absent from the environment is needed.
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6.3 Scan Types and their Changes

The AMEP system has inherited some strong scan processing algorithms from CANEWS 1, and has added new approaches to supplement and enhance them. These algorithms are applicable to EA both as regards to mode classification and mode change detection, in the following areas:

Scan Identification	a) EA for missile seeker search/acquisition denial. Here the scan must continue to be identified as continuous(search/acquisition) mode.
Scan Mode Change	see section on <i>Mode Change Detection</i>

II. AMEP Design and Implementation Concepts

The AMEP project has generated experience with new processing and implementation techniques, some of which may be applicable to the Effectiveness Assessment problem. Amongst these are the blackboard approach to the derivation and representation of solutions, the Dempster-Shafer approach to uncertainty management, the representation of expected events as parts of scripts, hypothetical reasoning, and object-oriented classification technologies. These techniques are discussed and related to the EA problem in the sub-sections below. This section does not directly address the uses of these approaches within AMEP, but rather the areas wherein they may prove

) applicable to the EA problem in the EWCP.

i. Blackboard Techniques

Blackboard techniques are particularly well suited to integrating a number of solution processes which are at work on aspects of the same problem, using partly shared and partly independent data. The blackboard can be viewed as a global data base which allows data to be stored and accessed at disparate times in a controlled manner. This matches well with the type of problem faced in the EWCP's effectiveness assessment. The solution of the problem evolves as the "state of the blackboard". It can be read at any time and metrics or thresholds applied to decide whether an acceptable solution has been reached. Given that many algorithms, rules and forms of evidence must be applied in the EA process, such an architecture may prove valuable. In particular, it is expected that EA in the EWCP will often be applied to the results of a combination of Electronic Countermeasures (ECM) techniques, using measurements from a combination of sensor systems.

) The Blackboard systems of the AMEP are very well organized into multiple generic levels with concurrent Actors providing the processing (expertise), and are nicely implemented according to the object-oriented paradigm. These aspects could be used intact or treated as an "executable specification" for re-implementation in the EWCP. The expression of the expertise of the Actors is a current weakness within the AMEP, as it is strictly algorithmic (rather than declarative); moreover, these algorithms tend to be distributed with rather fine granularity amongst multiple related methods (cf: procedures) of multiple classes. These observations do not by any means negate the value of this very strong area in the AMEP; they are indications of areas to be refined.

ii. Dempster-Shafer Uncertainty Management

The Dempster-Shafer (DS) theory of evidence has been applied in several areas within the AMEP, especially in the TSA.

This Uncertainty Management System (UMS) has been the subject of extensive research leading to a number of variants and optimizations. The salient features which make it interesting for the EA area of EWCP are its mathematical rigour and its ability to distribute evidence consistently amongst various competing interpretations of the measured environment.

) Some form of UMS will be needed in the EA area because of the ambiguity and incompleteness of the measured data. Given this, the DS system is certainly a candidate worth considering, especially in light of the fact that it has been refined for both performance and flexibility within AMEP (at the cost of a tolerably small loss of accuracy due to approximation). The open question is whether this is indeed the best choice for EWCP's UMS. The DS system can be rather computationally intensive for complex problems; although there have been optimizations within AMEP, it is not clear at this time that the paradigm is adaptable to the particular real-time

demands of EWCP. This entire area requires a rigorous requirements analysis and some analytical or experimental evaluation of the various alternative UMSs that could be used. Certainly, the AMEP experience can and should figure in this process.

iii. Scripts for Default Temporal Knowledge

An area which has reached an early prototype stage in the AMEP is the representation of default knowledge about the temporal sequencing of events (scenarios or parts thereof) in the form of scripts. This structure has the virtue of simplicity, and is amenable to pattern matching. It permits the system to anticipate future events based on partial matching of (the early section of) a script. Then, when the events occur, they can be interpreted as lending strong evidence in support of both the whole script, and its later (temporally future) portions.

Scripts can serve to unify views of the situation over time, and can alleviate some of the burden of real-time processing. In this latter regard, there is a cross-over point of the costs and benefits, depending upon the amount of pruning (of solution possibilities) that can safely be performed on the basis of a trusted script match and upon the actual processing cost of scripts. This processing cost, for fully implemented scripts, is not yet known but may be forthcoming from the near-term AMEP experience. The amount of pruning that is safe may remain a moot point, since for the time being at least the AMEP system eschews pruning in most circumstances to take the cautious though costly route of preserving as much information as possible.

Given the challenges of sensor data fusion inherent in the EA problem (amongst others within EWCP's domain), scripts need to be considered as a processing technique to be integrated with others. This is particularly true if a relatively rich system of evidence such as DS beliefs or Fuzzy Logic is chosen: the on-going match to a script can be construed as lending greater and greater evidence to the veracity of the hypothesis upon which the script is based, and of the events expected towards the end of the script.

iv. Hypothetical Reasoning

Hypothetical reasoning is used in several places within the AMEP, particularly in connection with blackboards and DS beliefs. They constitute a form of Truth Maintenance System (TMS), for rudimentary non-monotonic reasoning. Non-monotonic reasoning systems preserve enough information to undo the inferences made while executing an algorithm, and to re-instate a previous state of the reasoning process. On the AMEP blackboards, all information but the fundamental measurements supplied by the radar equipment is represented in the form of hypotheses.

The applicability of non-monotonic reasoning to the EA problem area is beyond dispute. Whether the particular form of TMS adopted by the AMEP system is applicable to EWCP is unclear. Its real-time performance in AMEP has still not been adequately characterized, and the real-time constraints of the EA aspect of EWCP need study. If the constraints are hard to meet,

various simplifications can be adopted to provide a degree of non-monotonicity without a full-fledged TMS. (In the extreme, many older systems simply do without it.) Moreover, the process for undoing hypotheses within the AMEP is still rather complex and dependent on the application developer's discipline (cf: error-prone). This is a weakness similar in severity to the absence of declarative techniques for expressing expert knowledge; one can live with the situation, but it is risky and costly for both development and maintenance.

In summary, this is once again an area where the lessons learned from the AMEP experience must be combined with a process requirements analysis and with evaluation of the alternatives.

v. Object-oriented Classification

The identification process within the AMEP makes use of a novel, object-oriented classification technology wherein the various classes that may match an entity compete to be allowed to claim it as their type. They each attempt to construe the object to be identified as being of their own class, expressing the goodness of the match in terms of evidence in the DS system. At the next higher level, the system then chooses the winner to be the class which has amassed the most such evidence; alternatively, the system can retain the complete list (less the certain negatives), ordered by weight of evidence.

This system is completely consistent with the AMEP philosophy concerning the retention and use of competing views of the (uncertain and incomplete) environment. As such, in theory, it is directly applicable to the problems of EA with uncertain and incomplete information. That the algorithms involved make heavy use of inheritance tends to make them hard to port to languages which are not fully object-oriented. Versions of Ada 9x are now available, featuring inheritance; C++ and Smalltalk already handle it. The use of most other languages would preclude the use of these algorithms.

As a rather subjective judgment, the philosophy and concept of these AMEP algorithms is laudable, but they can probably be realized in a more efficient manner than through inheritance.

7 Uncertainty Management Systems and AI Applications

7.1 Uncertainty management systems

7.1.1 Introduction

In the problem domain addressed by EWCP, the input data to computation is characterized by uncertainty and incompleteness. If we consider figure 7-1, we see that uncertainties arise both outside EWCP, affecting its input data, and within EWCP arising from incomplete and erroneous knowledge and from possible time-line effects of processing delays. Outside EWCP the uncertainties arise (as a minimum) from the sensors' resolution and accuracy as well as their system and environmental noise. Additional uncertainties are then introduced by the data fusion process. Not explicitly illustrated are the uncertainties in the whole system which can be introduced by bus errors, processing speed mismatches, etc. leading to missing, corrupt or conflicting data and commands. Internally to EWCP, the expression of knowledge is sure to require some representation for the uncertainty about the validity of that knowledge, and some calculus for the adjustment of this uncertainty to varying applications of the knowledge (its validity in context).

These uncertainties can give rise to a multitude of special cases which must be dealt with in the algorithms of the software. Rather than handling the algorithmic anomalies individually in an ad hoc manner, using many program statements to deal with them in various distributed parts of the software, it is preferable to identify a consistent and global Uncertainty Management System (UMS). Such a system can, in principle, be used throughout the software, with few or no exceptions and ad hoc adjustments. The usage might be on the basis of a few function calls provided as a system-wide software service to enable consistent management of the uncertainties. It might also, perforce, be more complicated than this; but at the least it should be consistent, clear, and available throughout the system.

It would be desirable to have a UMS which is consistent throughout the whole system rather than just EWCP; in this regard, a minimum requirement is that the mapping of externally-provided uncertainty measures into the EWCP UMS must be well-understood and correctly handled. In the absence of a truly global system, EWCP certainly requires its own internal UMS which is capable of representing and performing calculations with the uncertainties associated with the knowledge and its application.

Two candidates for the basis of the UMS are Dempster-Shafer calculus and Fuzzy Logic. They are quite widely separated from each other in theoretical basis, but both are well supported with theory, and both are paradigms from which many other systems of uncertainty have been derived as special cases. In the following sections we examine a simple problem handled by the two systems, to see how uncertainties might be represented and compounded in each.

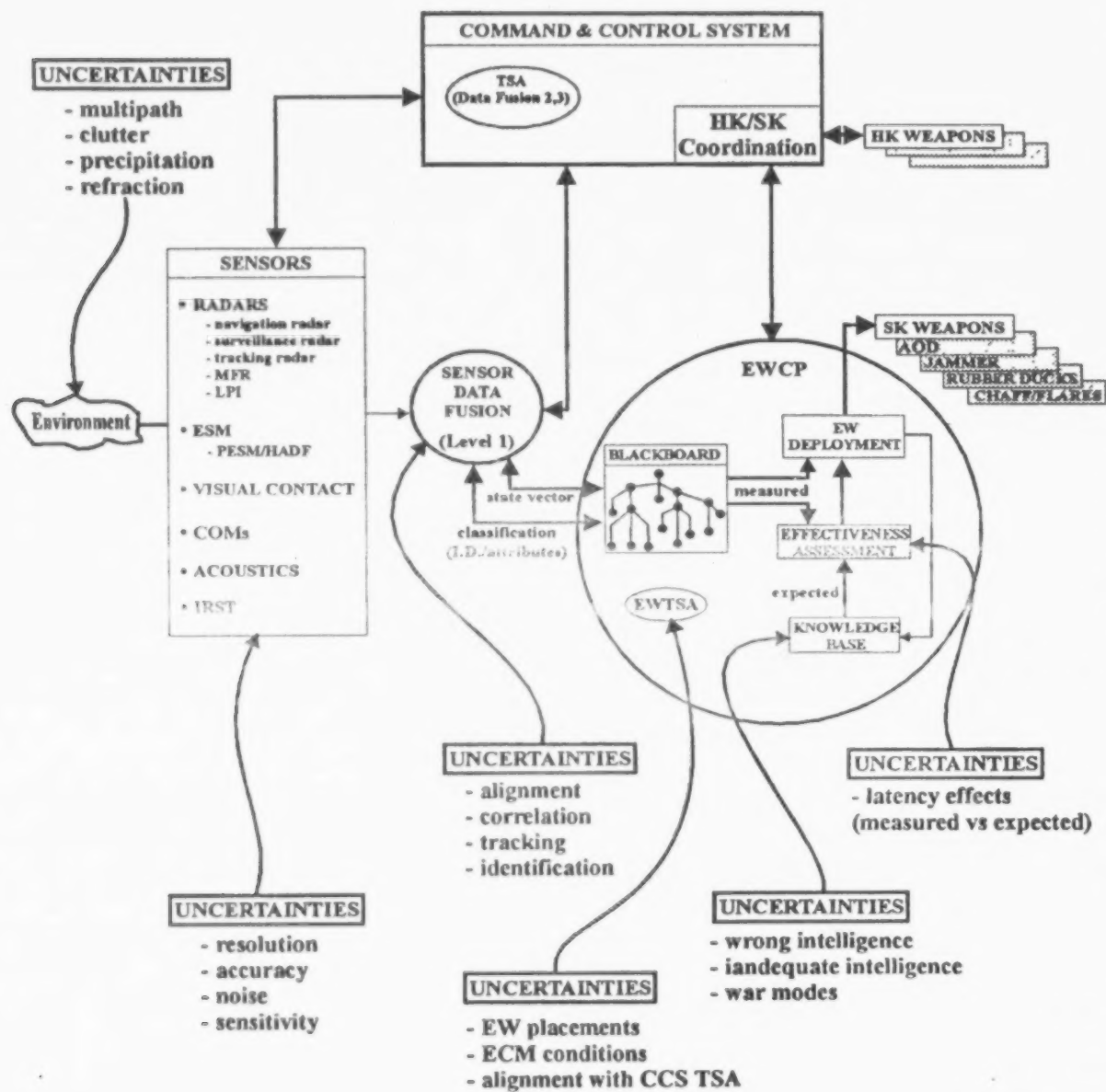


Figure 7-1 Uncertainties associated with EWCP

7.1.2 Example Scenario

A very small example scenario is presented to support examples of inferencing with the various candidate systems of uncertainty handling. See figure 7-2. An emitter moves through space in relation to the sensor platform. Angular measurements are received at times 0 through 6. The trajectory of the emitter may follow a direct, targetting path to the sensor platform, or it may follow a path which deviates towards the chaff cloud. The problem is to perform effectiveness assessment for the chaff deployment (and any other countermeasures which may have been used along with it).

For simplicity, the following exposition does not attempt to represent any existing implementation, but establishes the models based upon Dempster-Shafer and Fuzzy Logic theories using a simple design for each.

7.1.3 The Fuzzy Logic Model

Fuzzy logic is an extension of classical and boolean logics to the case of membership functions which have a range of values rather than the discrete pairs [0,1] or [True,False]. This can be interpreted as partial, or "fuzzy" membership: "tall" might mean 5'10" or 6'7" and can be distinguished by a degree of membership which is neither zero nor 1. Boolean logic is a special case of fuzzy logic.

Fuzzy logic operations are generalizations of their boolean counterparts. The fuzzy logic operations of interest in this example are defined as follows:

AND over a set is the MIN operation on the set

OR over a set is the MAX operation on the set

NOT over a set is the subtraction of each member from the MAX in the universe (1).

Implication is (as in boolean logic) $A \rightarrow B$ equivalent to $(\text{NOT } A) \text{ OR } B$.

The operations above between two sets are performed on the corresponding members of each set, and yield a new set whose members are the results of these individual operations.

7.1.3.1 Example scenario using fuzzy logic

We will assume that the angular measurements are made by a system which has an accuracy of 0.25 degrees, and the reliability of whose measurements have some nominal confidence, or probability of correctness. We capture both the accuracy and the confidence in a membership function for the fuzzy set of interest: the set of angles near to any given angle. See figure 7-3. Given any angle, this function returns, for a distance in degrees from that angle, the degree of "closeness" to the given angle. This degree is taken as the degree of membership in the set, and it ranges from 0 to 1. Note that it is symmetrical about the zero distance point. Note also that it is not discrete in the resolution steps of the equipment. This will allow us to handle nominal

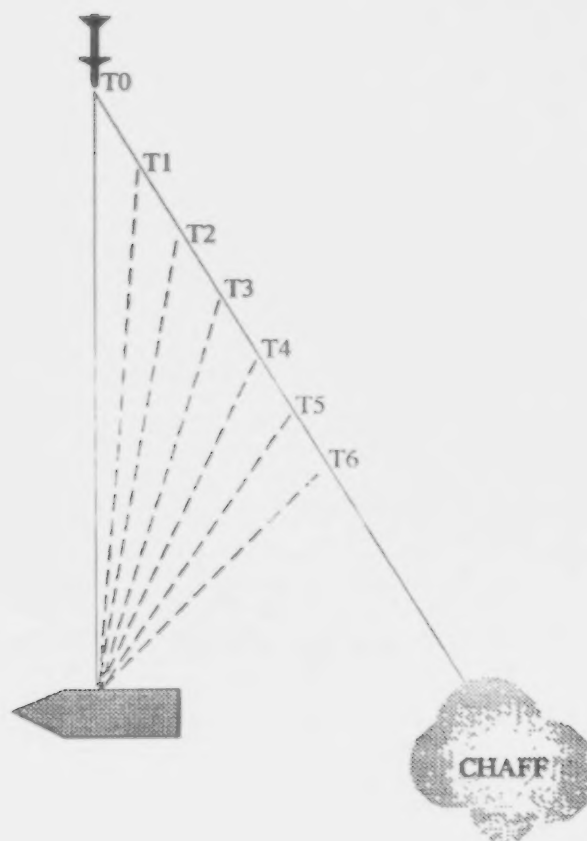


Figure 7.2 Example scenario

expected measurements which are not expressed in the resolution cells of the equipment, and it also expresses the probabilistic aspects of the equipment characteristic: there is some probability that measurements returned in the 0 degree resolution cell are not actually at 0 degrees precisely. The resolution cells are noted using vertical hatched lines, and the function is piecewise linear to simplify calculation of the values for the example.

Given a distance of 100 meters between the ship and its chaff cloud, a range of 15 kilometers at T0, a missile speed of 300 m/s, it can be calculated that the angular changes along the path to the chaff cloud will be 0.023 degrees at T1 (1 second), 0.127 degrees at T2 (5 seconds), 0.287 degrees at T3 (10 seconds), 0.49 degrees at T4 (15 seconds), 0.76 degrees at T5 (20 seconds), and 1.72 degrees at T6 (30 seconds). This is taken from Table 1. The angular changes along the path to the ship will all be zero, since we neglect ship motion for this example, and also assume that the chaff cloud does not blow further away.

Range (km)	Time (sec)					
	1	5	10	15	20	30
15	0.023	0.127	0.287	0.49	0.76	1.72
20	0.013	0.069	0.152	0.25	0.37	0.70
25	0.008	0.04	0.09	0.15	0.22	0.40
30	0.006	0.03	0.06	0.101	0.143	0.25
35	0.0042	0.022	0.046	0.073	0.102	0.17

A good system of uncertainty management would not allow a distinction to be drawn before the resolution of the equipment makes it sensible. In our example the 0.25 degree resolution cell should preclude any decision before at least T2, assuming the missile is either on the targetting or the seduced path. If it is on some much different path, then we should see the difference sooner.

The strategy will be to measure the angular change at each time, and compare it to the ideal deviation towards the chaff cloud, as well as to the 0 degree deviation which would indicate failure of the countermeasures. Using the same membership function, we can express an uncertainty about our calculation of the ideal deviations. Some variation around the ideal might still represent a real-world seduced response by the missile. For example, a 0.8 membership value for nearness to the expected value would allow about half a degree of "play" around our calculated expected values.

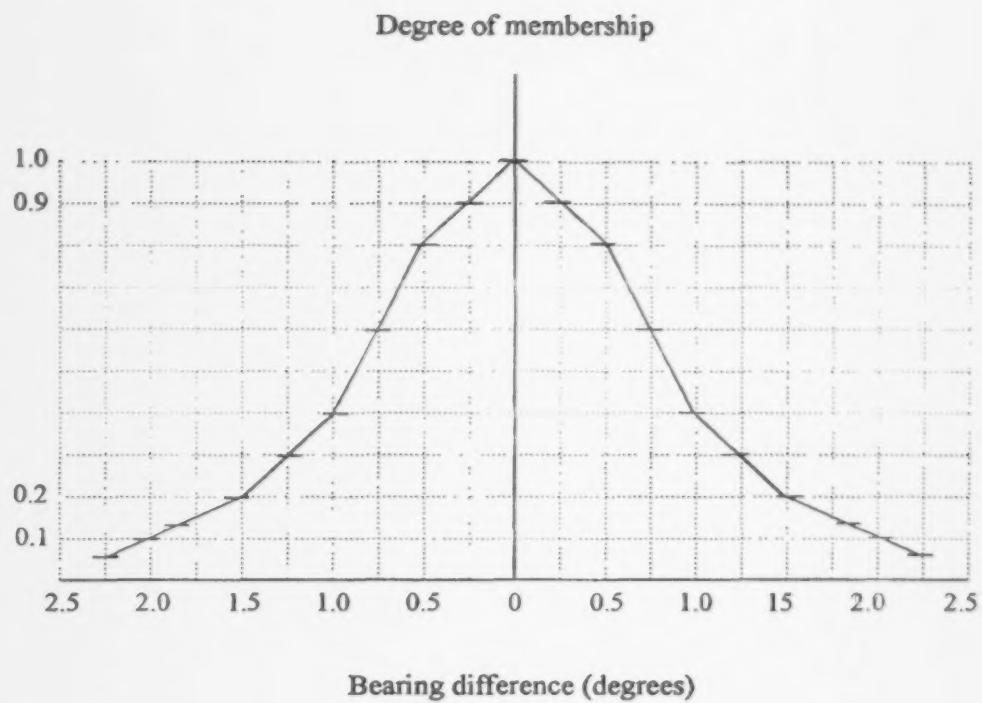


Figure 7-3 A membership function for bearing

We will compare the measured angles with each of the expected values, that for the path which targets the sensor platform, and that for the path which deviates towards the chaff cloud. In order to do this we will pose the logical query: To what extent does the expected value, E, imply the measured value, M? The logical implication, in this context, serves to establish the sufficiency of the expected value to explain the measured value. Note that the phrase "to what extent" is indicative of the fuzzy nature of the implication, since such a phrase would not appear in a standard logical query. Note also that it is the responsibility of an expert system or function to precalculate the expected path, given knowledge of countermeasure deployment and platform and missile motion. It is also possible (and generally quite useful) to calculate the extent to which the set of all other paths (i.e. NOT the Expected Targetting path, ET, AND NOT the Expected Deviating path, ED) is sufficient to explain the measurements. To obtain the description of this other space, we need only perform the logical operations mentioned in parentheses, using the rules of fuzzy logic.

The fuzzy membership values for the results of performing $m(E) \rightarrow m(M)$ with the three versions of E will be used to decide which path the system holds the missile to be following. Given the membership function we are using, and the resolution of the angular measurement system, we can only declare a winner if there is a difference of more than 0.1.

We can now proceed to show the results of applying fuzzy logic to the above scenario. We will do it for the case of the missile following the expected seduced path exactly (within the resolution of our equipment), and the case of the missile following a similar but not exact path (reflected in a different set of measurements).

Missile on exact seduced path:

Membership of measures in Expected Deviating path:

Time	Measured	ED (seduced)	Difference	Membership
T1	0 degrees	0.023	0.023	0.991
T2	0.25	0.127	0.123	0.951
T3	0.25	0.287	0.037	0.985
T4	0.5	0.49	0.01	0.996
T5	0.75	0.76	0.01	0.996
T6	1.75	1.72	0.03	0.988

Membership of measures in Expected Targetting path:

Time	Measured	ET (targetting)	Difference	Membership
T1	0 degrees	0	0	1
T2	0.25	0	0.25	0.9
T3	0.25	0	0.25	0.9
T4	0.5	0	0.5	0.8
T5	0.75	0	0.75	0.6
T6	1.75	0	1.75	0.15

Now to perform the logical implication, we could take $m(E)$, E's membership in the expected path, to be 1; however, we will introduce our uncertainty about this by letting E's membership be 0.7, as outlined above. Recall that $m(E) \rightarrow m(M)$ will be evaluated using $(\text{NOT } m(E)) \text{ OR } m(M)$.

Time 1:

Deviating: $(1 - 0.7) \text{ OR } 0.991 = 0.3 \text{ OR } 0.991 = 0.991$
 Non-Deviating: $(1 - 0.7) \text{ OR } 1.0 = 0.3 \text{ OR } 1.0 = 1.0$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.991) \text{ AND } (1 - 1))$
 $= 0.3 \text{ OR } (0.09 \text{ AND } 0) = 0.3 \text{ OR } 0 = 0.3$

Time 2:

Deviating: $(1 - 0.7) \text{ OR } 0.951 = 0.3 \text{ OR } 0.951 = 0.951$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.9 = 0.3 \text{ OR } 0.9 = 0.9$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.951) \text{ AND } (1 - 0.9))$
 $= 0.3 \text{ OR } (0.049 \text{ AND } 0.1) = 0.3 \text{ OR } 0.049 = 0.3$

Time 3:

Deviating: $(1 - 0.7) \text{ OR } 0.985 = 0.3 \text{ OR } 0.985 = 0.985$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.9 = 0.3 \text{ OR } 0.9 = 0.9$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.985) \text{ AND } (1 - 0.9))$
 $= 0.3 \text{ OR } (0.015 \text{ AND } 0.1) = 0.3 \text{ OR } 0.015 = 0.3$

Time 4:

Deviating: $(1 - 0.7) \text{ OR } 0.996 = 0.3 \text{ OR } 0.996 = 0.996$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.8 = 0.3 \text{ OR } 0.8 = 0.8$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.996) \text{ AND } (1 - 0.8))$
 $= 0.3 \text{ OR } (0.004 \text{ AND } 0.2) = 0.3 \text{ OR } 0.004 = 0.3$

Time 5:

Deviating: $(1 - 0.7) \text{ OR } 0.996 = 0.3 \text{ OR } 0.996 = 0.996$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.6 = 0.3 \text{ OR } 0.6 = 0.6$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.996) \text{ AND } (1 - 0.6))$
 $= 0.3 \text{ OR } (0.004 \text{ AND } 0.4) = 0.3 \text{ OR } 0.004 = 0.3$

Time 6:

Deviating: $(1 - 0.7) \text{ OR } 0.988 = 0.3 \text{ OR } 0.988 = 0.988$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.15 = 0.3 \text{ OR } 0.15 = 0.3$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.988) \text{ AND } (1 - 0.15))$
 $= 0.3 \text{ OR } (0.012 \text{ AND } 0.85) = 0.3 \text{ OR } 0.012 = 0.3$

Missile on exact seduced path:

Membership of measures in Expected Deviating path:

Time	Measured	ET (seduced)	Difference	Membership
T1	0 degrees	0.023	0.023	0.991
T2	0	0.127	0.127	0.949
T3	0.5	0.287	0.213	0.915
T4	0.5	0.49	0.01	0.996
T5	1.0	0.76	0.24	0.904
T6	1.5	1.72	0.22	0.912

Membership of measures in Expected Targetting path:

Time	Measured	ET (targetting)	Difference	Membership
T1	0 degrees	0	0	1
T2	0	0	0	1
T3	0.5	0	0.5	0.8
T4	0.5	0	0.5	0.8
T5	1.0	0	1.0	0.4
T6	1.5	0	1.5	0.2

Time 1:

Deviating: $(1 - 0.7) \text{ OR } 0.991 = 0.3 \text{ OR } 0.991 = 0.991$
 Non-Deviating: $(1 - 0.7) \text{ OR } 1.0 = 0.3 \text{ OR } 1.0 = 1.0$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.991) \text{ AND } (1 - 1))$
 $= 0.3 \text{ OR } (0.09 \text{ AND } 0) = 0.3 \text{ OR } 0 = 0.3$

Time 2:

Deviating: $(1 - 0.7) \text{ OR } 0.949 = 0.3 \text{ OR } 0.949 = 0.949$
 Non-Deviating: $(1 - 0.7) \text{ OR } 1.0 = 0.3 \text{ OR } 1.0 = 1.0$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.949) \text{ AND } (1 - 1))$
 $= 0.3 \text{ OR } (0.051 \text{ AND } 0) = 0.3 \text{ OR } 0 = 0.3$

Time 3:

Deviating: $(1 - 0.7) \text{ OR } 0.915 = 0.3 \text{ OR } 0.915 = 0.915$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.8 = 0.3 \text{ OR } 0.8 = 0.8$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.915) \text{ AND } (1 - 0.8))$
 $= 0.3 \text{ OR } (0.085 \text{ AND } 0.2) = 0.3 \text{ OR } 0.085 = 0.3$

Time 4:

Deviating: $(1 - 0.7) \text{ OR } 0.996 = 0.3 \text{ OR } 0.996 = 0.996$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.8 = 0.3 \text{ OR } 0.8 = 0.8$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.996) \text{ AND } (1 - 0.8))$
 $= 0.3 \text{ OR } (0.004 \text{ AND } 0.2) = 0.3 \text{ OR } 0.004 = 0.3$

Time 5:

Deviating: $(1 - 0.7) \text{ OR } 0.904 = 0.3 \text{ OR } 0.904 = 0.904$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.4 = 0.3 \text{ OR } 0.4 = 0.4$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.904) \text{ AND } (1 - 0.4))$
 $= 0.3 \text{ OR } (0.096 \text{ AND } 0.6) = 0.3 \text{ OR } 0.096 = 0.3$

Time 6:

Deviating: $(1 - 0.7) \text{ OR } 0.912 = 0.3 \text{ OR } 0.912 = 0.912$
 Non-Deviating: $(1 - 0.7) \text{ OR } 0.2 = 0.3 \text{ OR } 0.2 = 0.3$
 Other: $(1 - 0.7) \text{ OR } ((1 - 0.912) \text{ AND } (1 - 0.2))$
 $= 0.3 \text{ OR } (0.088 \text{ AND } 0.8) = 0.3 \text{ OR } 0.088 = 0.3$

7.1.3.2 Comments on the fuzzy logic model:

In the case of the missile following the ideal path to the chaff cloud, we obtain a distinct indication of this at T4 (time four), fifteen seconds into the scenario. This is completely consistent with the original data, the assumed precision of the equipment, and our assumptions about the accuracy of our idealized path calculations. In the case of the missile following another path, we obtain the decision at T3, ten seconds into the scenario, because of the particular way

in which the missile deviated from the expected path. In both cases, we are aware from the outset that the angular deviations are only consistent with the paths to the ship or the chaff cloud. The rest of the compass is ruled out immediately.

The computations necessary to implement the logic are almost trivial, and the steps necessary to include uncertainty about the expected path are easy because the membership function used is the same. If other pieces of equipment were used to provide concurrent measurements, and the sets of measurements were to be combined, we would need to analyze the various membership functions (assuming more than one) to ensure the consistency of the values produced by them. Having dealt with this mapping at the outset, the remainder of the uncertainty handling in the combined system reduces to simple logical operations. Arbitrarily large inference networks can be traversed without fear of inconsistency.

The relationship between fuzzy membership values and probabilities is not direct, and should not be insisted upon if fuzzy logic is to be used to advantage. Recall that fuzzy logic is the general case of Boolean logic, not of probability. It is instructive, however, to keep some of the issues surrounding probability in mind when designing the logic of a system. Where the measurements being combined are intended to pertain to the same external event, they would be dependent in the probabilistic sense, and the MIN function used in performing the fuzzy logical AND is appropriate even in the probabilistic view. One should note, however, that if evidence is independent and a probabilistic meaning is intended, the value returned by an AND function should be less than or equal to that returned by MIN. Some systems of uncertainty management would return a value greater than MIN for the AND operation when combining supporting evidence for a single event. While this resembles a human response to uncertainty, the systems which do so tend to be heuristic and are difficult to support with consistent theoretical constructs. This often translates into a requirement to trap and handle exceptional cases at the level of the expert system itself, where it would be preferable to have them handled automatically (in effect, not to be exceptions) at the level of the UMS.

If any of the participating values in a fuzzy logic operation are subsequently revised, the operation must be performed again. Thus, if our certainty about our expected path became lower for Time 2, we would have to perform three implication operations again for that time. Because the operations tend to be computationally small, this is not a heavy burden. This is not necessary for new evidence, as it can be combined with the existing results and the new result is guaranteed to be consistent with the previously computed answer. This is a feature of the use of MIN and MAX functions for OR and AND.

History of the mathematical computation is not preserved by the fuzzy logic system itself. The designer of the expert system would need to decide in what cases backtracking or world-view revision would be necessary, and ensure that the appropriate fuzzy memberships were preserved to enable these operations. In our example, the designer might consider it useful to keep track of a list of measurements from T0 to T6, so as to perform some higher-level inferencing about the missile trajectory. Alternatively, the designer could implement a real-time rule interpreter

and/or compiler, which directly supports both backtracking and fuzzy logical certainty factors. In this case, the undoing of the logical operations (and preservation of intermediate fuzzy results) becomes automatic with backtracking.

7.1.4 The Dempster-Shafer model:

Introducing the Dempster-Shafer model is somewhat complex, and we assume the reader is comfortable with probability theory and set theory. We restrict the introduction to those definitions and observations necessary to establish the notation for this document and to elucidate the example.

Definitions for Dempster-Shafer:

Universe or Frame of Discernment: U , the set of all possible values for a variable; usually a finite set.

Proposition: an assertion corresponding to a subset of the Universe. The set of all possible assertions is the power set of the universe, $P(U)$.

Basic Probability Assignment: a function, $m:P(U) \rightarrow [0,1]$, such that $m(\text{EmptySet}) = 0$, and $\sum m(A) = 1$, over all propositions A contained in or equal to U . This is a representation of uncertain evidence about the value of some variable, X , which takes values in U . Note that $m(A)$ is not the value of the proposition "the value of X is in A ", but is rather the probability mass belonging a subset (proposition), A , in $P(U)$.

Focal Element: Each subset F of U which has $m(F) > 0$ is called a focal element of $P(U)$.

Belief: a function, $\text{Belief}:P(U) \rightarrow [0,1]$, such that $\text{Belief}(A) = \sum m(B)$, over all subsets B contained in or equal to A . This is the total probability mass belonging to A and its subsets.

Doubt:

$$\text{Doubt}(A) = \text{Belief}(\text{not}(A))$$

Plausibility:

$$\text{Plausibility}(A) = 1 - \text{Doubt}(A)$$

NOTE: Belief and Plausibility are often taken to be the lower and upper bounds, respectively,

of the probability.

Some Relations:

$$\text{Belief}(\text{EmptySet}) = 0$$

$$\text{Plausibility}(\text{EmptySet}) = 0$$

$$\text{Belief}(U) = 1$$

$$\text{Plausibility}(U) = 1$$

$$\text{Plausibility}(A) \geq \text{Belief}(A)$$

$$\text{Belief}(A) + \text{Belief}(\text{not}(A)) \leq 1$$

$$\text{Plausibility}(A) + \text{Plausibility}(\text{not}(A)) \geq 1$$

$$\text{Belief}(A) \leq \text{Belief}(B), \text{ where } A \text{ is contained in or equal to } B$$

$$\text{Plausibility}(A) \leq \text{Plausibility}(B), \text{ where } A \text{ is contained in or equal to } B$$

NOTE: If we consider $\text{Belief}(A)$ to be a measure of the mass of probability which must stay somewhere in A , the basic probability assignment specifies in more detail how this mass is distributed. When new evidence arrives, a new probability assignment becomes effective, and a new value of $\text{Belief}(A)$ can be computed, using Dempster's rule of combination.

Weight of Conflict: given two probability assignments, m_1 and m_2 , the weight of conflict is $w(m_1, m_2) = \sum m_1(X)m_2(Y)$, over all pairs, X and Y , of disjoint subsets of U (X intersection Y is the EmptySet). That is, the weight of conflict is a measure of the mass of combined probability ascribable to all pairs of disjoint subsets of U .

Orthogonal Sum: given two probability assignments, m_1 and m_2 , the orthogonal sum is given by,

$$\text{orth}_{m_1, m_2}(A) = (\sum_{X \cap Y \subseteq A} m_1(X)m_2(Y)) / (1 - w(m_1, m_2))$$

whenever A is not equal to the EmptySet. We define $\text{orth}_{m_1, m_2}(\text{EmptySet})$ to be zero so that the orthogonal sum is still a basic probability assignment.

Dempster's rule of combination: Another name for the orthogonal sum.

7.1.4.1 Example using Dempster-Shafer methods:

We will concern ourselves with the states T, S and O:

T: the missile is following the targetting path to the ship

S: the missile has been seduced to a path towards the chaff cloud

O: the missile is on some other path

We must consider propositions such as {T,S}, {S,O} and so on because of the necessity of evaluating the weight of conflict. Here we can consider the values ascribed to the set {T,S} for example, to represent the ambiguity in the measured information.

We cannot use the membership function as if it were a probability distribution, because the values would not sum to one across the propositions of interest; for example, at T1 there is a high membership value in both T and S, which sums to 1.991.

We will postulate a probability distribution for each measurement. This distribution should take into account the accuracy and precision of the measuring equipment, its false alarm rate, and any other stochastic processes deemed to be significant by the system designers. We will choose values somewhat arbitrarily in the example, since our focus is on the approach to managing the uncertainties; but the issue of how well the probabilities represent reality is extremely important. In combining evidence, the strategy will be to combine the uncertain information from each of the measurements in turn, and to look for a winning combination of plausibility and belief. It is the responsibility of the operator or an expert system to ensure that decisions are not made in favour of a strong belief if the plausibility of its negation is also very high.

For brevity we will examine only one combination of evidence. We will assume that the missile has moved along the path toward the chaff cloud. The basic probability assignments have not been rigorously derived from the system specifications and measurement errors, but have been chosen to be consistent with the seduced path. At time T4, m_i represents the basic probability assignment for measurements up to time T3, and m_4 that for the measurement made at T4:

Basic Probability Assignments at T4:

	EmptySet	{T}	{S}	{O}	{T,S}	{T,O}	{S,O}	{T,S,O}
m_1	0	0.2	0.2	0.2	0.1	0.1	0.1	0.1
m_2	0	0.18	0.24	0.18	0.09	0.09	0.12	0.1
$orth_{1,2}$	0	0.256	0.317	0.269	0.044	0.044	0.053	0.016

Note that although {T,S,O} only carries a small mass of probability in its own right, the sum of its own mass and that of all its subsets is in fact 1.0.

The orthogonal sum was generated as follows:

We calculate the weight of conflict as:

$$\begin{aligned}
 & m_1(T)m_2(S) + m_1(T)m_2(O) + m_1(T)m_2(\{S,O\}) \\
 & + m_1(S)m_2(T) + m_1(S)m_2(O) + m_1(S)m_2(\{T,O\}) \\
 & + m_1(O)m_2(T) + m_1(O)m_2(S) + m_1(O)m_2(\{T,S\}) \\
 & + m_1(\{T,S\})m_2(O) \\
 & + m_1(\{T,O\})m_2(S) \\
 & + m_1(\{S,O\})m_2(T) \\
 & = 0.2*0.24 + 0.2*0.18 + 0.2*0.12 \\
 & + 0.2*0.18 + 0.2*0.18 + 0.2*0.09 \\
 & + 0.2*0.18 + 0.2*0.24 + 0.2*0.09 \\
 & + 0.1*0.18 \\
 & + 0.1*0.24 \\
 & + 0.1*0.18 \\
 & = 0.048 + 0.036 + 0.024 \\
 & + 0.036 + 0.036 + 0.018 \\
 & + 0.036 + 0.048 + 0.018 \\
 & + 0.018 \\
 & + 0.024 \\
 & + 0.018 \\
 & = 0.36
 \end{aligned}$$

The denominator of the orthogonal product expressions, then, is $1 - 0.36 = 0.64$.

The numerators of the orthogonal sums are comprised of products of the probability masses from m_i and m_j for pairs of propositions whose intersection forms the proposition of interest. The numerator of the orthogonal sum for T is given by:

$$\begin{aligned}
 & m_i(T)m_j(T) + m_i(T)m_j(\{T,S\}) + m_i(T)m_j(\{T,O\}) + m_i(T)m_j(\{T,S,O\}) \\
 & + m_i(\{T,S\})m_j(T) + m_i(\{T,S\})m_j(\{T,O\}) \\
 & + m_i(\{T,O\})m_j(T) + m_i(\{T,O\})m_j(\{T,S\}) \\
 & + m_i(\{T,S,O\})m_j(T) \\
 = & 0.2*0.18 + 0.2*0.09 + 0.2*0.09 + 0.2*0.1 \\
 & + 0.1*0.18 + 0.1*0.09 \\
 & + 0.1*0.18 + 0.1*0.09 \\
 & + 0.1*0.18 \\
 = & 0.036 + 0.018 + 0.018 + 0.02 \\
 & + 0.018 + 0.009 \\
 & + 0.018 + 0.009 \\
 & + 0.018 \\
 = & 0.164
 \end{aligned}$$

The value for T, then, is $0.164/0.64 = 0.256$.

The numerator of the orthogonal sum for S is given by:

$$\begin{aligned}
 & m_i(S)m_j(S) + m_i(S)m_j(\{T,S\}) + m_i(S)m_j(\{S,O\}) + m_i(S)m_j(\{T,S,O\}) \\
 & + m_i(\{T,S\})m_j(S) + m_i(\{T,S\})m_j(\{S,O\}) \\
 & + m_i(\{S,O\})m_j(S) + m_i(\{S,O\})m_j(\{T,S\}) \\
 & + m_i(\{T,S,O\})m_j(S) \\
 = & 0.2*0.24 + 0.2*0.09 + 0.2*0.12 + 0.2*0.1 \\
 & + 0.1*0.24 + 0.1*0.12 \\
 & + 0.1*0.24 + 0.1*0.09 \\
 & + 0.1*0.24 \\
 = & 0.048 + 0.018 + 0.024 + 0.02 \\
 & + 0.024 + 0.012
 \end{aligned}$$

$$\begin{aligned}
 &+ 0.024 + 0.009 \\
 &+ 0.024 \\
 &= 0.203
 \end{aligned}$$

The value for S, then, is $0.203/0.64 = 0.317$.

The numerator of the orthogonal sum for O is given by:

$$\begin{aligned}
 &m_1(O)m_1(O) + m_1(O)m_1(\{T,O\}) + m_1(O)m_1(\{S,O\}) + m_1(O)m_1(\{T,S,O\}) \\
 &+ m_1(\{T,O\})m_1(O) + m_1(\{T,O\})m_1(\{S,O\}) \\
 &+ m_1(\{S,O\})m_1(O) + m_1(\{S,O\})m_1(\{T,O\}) \\
 &+ m_1(\{T,S,O\})m_1(O) \\
 &= 0.2*0.18 + 0.2*0.09 + 0.2*0.12 + 0.2*0.1 \\
 &+ 0.1*0.18 + 0.1*0.12 \\
 &+ 0.1*0.18 + 0.1*0.09 \\
 &+ 0.1*0.18 \\
 &= 0.036 + 0.018 + 0.024 + 0.02 \\
 &+ 0.018 + 0.012 \\
 &+ 0.018 + 0.009 \\
 &+ 0.018 \\
 &= 0.172
 \end{aligned}$$

The value for O, then, is $0.172/0.64 = 0.269$.

The numerator of the orthogonal sum for {T,S} is given by:

$$\begin{aligned}
 &m_1(\{T,S\})m_1(\{T,S\}) + m_1(\{T,S\})m_1(\{T,S,O\}) \\
 &+ m_1(\{T,S,O\})m_1(\{T,S\}) \\
 &= 0.1*0.09 + 0.1*0.1 \\
 &+ 0.1*0.09 \\
 &= 0.009 + 0.01 + 0.009 \\
 &= 0.028
 \end{aligned}$$

The value for {T,S} then, is $0.028/0.64 = 0.044$.

The numerator of the orthogonal sum for {T,O} is given by:

$$\begin{aligned} & m_i(\{T,O\})m_i(\{T,O\}) + m_i(\{T,O\})m_i(\{T,S,O\}) \\ & + m_i(\{T,S,O\})m_i(\{T,O\}) \\ & = 0.1*0.09 + 0.1*0.1 \\ & \quad + 0.1*0.09 \\ & = 0.009 + 0.01 + 0.009 \\ & = 0.028 \end{aligned}$$

The value for {T,O}, then, is $0.028/0.64 = 0.044$.

The numerator of the orthogonal sum for {S,O} is given by:

$$\begin{aligned} & m_i(\{S,O\})m_i(\{S,O\}) + m_i(\{S,O\})m_i(\{T,S,O\}) \\ & + m_i(\{T,S,O\})m_i(\{S,O\}) \\ & = 0.1*0.12 + 0.1*0.1 \\ & \quad + 0.1*0.12 \\ & = 0.012 + 0.01 + 0.012 \\ & = 0.034 \end{aligned}$$

The value for {S,O}, then, is $0.034/0.64 = 0.053$.

The numerator of the orthogonal sum for {T,S,O} is given by:

$$m_i(\{T,S,O\})m_i(\{T,S,O\}) = 0.1*0.1 = 0.01$$

The value for {T,S,O}, then, is $0.01/0.64 = 0.016$.

7.1.4.2 Comments on the Demspter-Shafer approach

Because of the lengthy calculations involved, we have chosen just one time step, about the point at which we would expect a winning belief to emerge. The other measurements can be combined with the current probability assignment in the same way.

To assess the current view of the situation, we use $m_i = \text{orth}_{i,j}$, and calculate the belief and plausibility functions. The beliefs in S and T are given by their basic probability assignments. The plausibilities require that we calculate the doubts, $\text{Belief}(\text{not}(S))$, and $\text{Belief}(\text{not}(T))$. These are given by:

$$\text{Belief}(S) = 0.317$$

$$\text{Belief}(\text{not}(S)) = \text{Belief}(\{T, O\}) = 0.044 + 0.269 + 0.256 = 0.569$$

$$\text{Plausibility}(S) = 1 - 0.569 = 0.431$$

$$\text{Belief}(T) = 0.256$$

$$\text{Belief}(\text{not}(T)) = \text{Belief}(\{S, O\}) = 0.053 + 0.317 + 0.269 = 0.639$$

$$\text{Plausibility}(T) = 1 - 0.639 = 0.361$$

$$\text{Belief}(O) = 0.269$$

$$\text{Belief}(\text{not}(O)) = \text{Belief}(\{T, S\}) = 0.044 + 0.256 + 0.317 = 0.617$$

$$\text{Plausibility}(O) = 1 - 0.617 = 0.383$$

In this example, at Time 4, the path towards the chaff cloud (S) can be chosen as a winner both on the basis of belief and plausibility. This is what we expect and desire. Whether the margin is adequate is a question which is not simple to answer. Our values for m_i and m_j were chosen rather arbitrarily, but in a manner that ought *a priori* to be consistent with the missile moving along the path which deviates towards the chaff cloud. The system would require some function which could develop the basic probability distributions from the raw measurements, and we have begged the question of the nature of that function. Given such a function, however, one could derive the spread of values which would permit a decision on which path is being taken. We could also choose to sidestep the problem of this threshold by saying that the system will only order the possible answers based on belief and plausibility, and not choose the winner itself. The ordering, however, is potentially difficult since not all examples will show as clear a winner as ours. The plausibility of the most believed proposition is not guaranteed to be the highest plausibility. If the system shows proposition A having the highest belief, but the plausibility of $\text{not}(A)$ is also very high, we should be reluctant to make life and death decisions.

7.1.5 Comparisons and observations:

Because of the different theoretical backgrounds of fuzzy logic and the Dempster-Shafer calculus, we cannot compare the results in our example directly and say "this one gave us a better answer" or "this one developed an answer sooner". To set up such a comparison would require a much more rigorous system definition, and a mapping between the fuzzy logic membership function and the function which assigns the basic probabilities in the Dempster-Shafer version. In effect we would have to carry out a system design exercise, derive the functions rigorously based on this, and then satisfy ourselves either analytically or experimentally that the membership function and the basic probability assignments were equivalent in some way. In fact, it is very likely that the clarity and timeliness of the answers will be more strongly dependent on the measurement system's precision and accuracy than on the particular system of uncertainty management that is chosen.

What we can see rather clearly from the examples is the orthogonal starting points of the two systems. They are the extrema of a spectrum of possible choices for a UMS. One generalizes classical logic (fuzzy logic) and the other generalizes classical probability (Dempster-Shafer). There are also a number of intermediate possibilities which simplify or hybridize them using heuristics. Dempster-Shafer calculus in particular has been the subject of much research leading to various optimizations and simplifications for special classes of evidence.

The meaning of fuzzy logic membership values is less familiar than the probabilistic expressions of Dempster-Shafer. The meaning of Dempster-Shafer results are more immediately grasped by scientists and engineers trained in classical probabilities. This does not necessarily make them easier for an expert system to use, although the completeness and rigour of the full Dempster-Shafer theory is appealing especially when one considers (in a general sense without reference to any particular system) multiple layers of logical inferences with uncertainty involved. On the other hand, the simplicity of fuzzy logic and its direct relationships to set theory and Boolean logic can give practitioners a similar sense of confidence. At the bottom, both theories are well developed, and this reduces to an emotional issue, not germane to the selection of UMS unless schedule, staff and training issues force its consideration.

In fact, criteria for making a selection are hard to identify. One might be the likelihood that the system can function within its real-time constraints. Others, like the need to undo inferences or applications of evidence, are highly dependent on system requirements and design, so we must deal with them here only in general.

The fuzzy logic approach definitely involves less computation. The number of sets which must

be dealt with in the Dempster-Shafer calculus is generally much larger, and the summation-of-products operations are more computationally intensive than the fuzzy logic operations. There exist optimizations of Dempster-Shafer, about which we will comment below.

When new evidence is added, the systems work differently. In fuzzy logic, the computations are carried out over the sets of interest each time a measurement is made, so that the weight of previous evidence is not automatically brought to bear. This might need to be extended by the system to a second level of fuzzy logic working on the measurement history; the motivation for this might be to prevent extreme outliers from causing temporary false alarms. In the Dempster-Shafer calculus, the previous evidence is combined with the new evidence in an automated manner so that the problem of spurious outliers in the measurements would be less troublesome (though not guaranteed to be fully solved); the computational load to achieve this is much greater, however.

In neither system is it particularly easy to undo the effects of old evidence that is proved to be erroneous. While the Dempster-Shafer system allows one to add a new piece of evidence with a counterbalancing basic probability assignment, it is not obvious how one would develop this assignment unless the history of the previous assignments has been kept. Equivalently, in the case of fuzzy logic, the history of fuzzy memberships would need to have been kept, so that the calculation could be redone. It might not be necessary to do this, however, in a case like our example. Only if another level of logic is being applied to the measurement history would we need to redo any calculations previous to the current time.

Both systems require to be tightly integrated with, or even managed by, an expert system of some kind. There is as yet no standard practice in this regard. The implementation of the UMS is a system design issue, and its application must be considered in conjunction with other system requirements and designs. The Dempster-Shafer calculus can only be used in complex real-time systems in one of its modified forms, for performance reasons. The choice and implementation of the modifications must be justified based on these other system requirements and designs. The fuzzy logic system is only applicable if the logical operations it is to execute are clearly defined, so it too is highly dependent on the rest of the system. Fuzzy logic is amenable to tight integration with an inference engine in which case its application could be largely transparent to the developers; such an inference engine, however, would probably have to be custom-developed. There is currently no black-box global solution to the UMS problem which can be provided at the outset and used without expertise by all design and implementation engineers. Whichever system is chosen, its application will require careful analysis throughout the development cycle of the system in which it is embedded.

Deriving the basic probability assignments is not trivial. Because the membership function is intended to be heuristic, it is probably a bit easier to obtain. However, it needs to be sensible, and if multiple devices are to be applied to a single external event, the membership functions provided by all of the devices should be reasonably consistent. More is embedded in the basic probability assignment. Consider the case of two sensors reporting on the same event. In fuzzy logic, the (expert) system must specify the nature of the logical operation -- do we consider that either one sensor OR the other is adequate, or must we have one AND the other. As long as the membership functions ("nearness" in our example, compounded with some uncertainty about the device) are comparable, both operations can be done, and the choice is one about which the system can reason based on the nature of the devices and other applicable knowledge. In the Dempster-Shafer case, there will be no difference in the basic way the evidence is combined. What may differ is the number of states of interest in the universe, U , and the values in the basic probability assignments.

While we have dealt with two approaches to uncertainty management in isolation from each other, the appropriate choice for EWCP may finally be a hybrid of them, or of modified versions of them. Such hybridization could be accomplished in various ways. In one, the outputs of each system are mapped to the inputs of the other, so that subsystems can use the system most appropriate to themselves, and pass their results along without loss. The mapping, as mentioned elsewhere in this document, may be non-trivial; in the worst case it may involve unrecoverable information loss at each conversion. In another approach, a small expert system could be implemented to monitor overall system traffic and select one or the other of the systems in order to meet real-time constraints. A data conversion is still necessary but is much less frequent, and might permit storage of system state at the time of the switch so that in quiet times the more time-consuming UMS could be re-instated and rolled forward. In a third approach, either system could be used locally to subsystems, but with the express design goal of creating output that can be consumed by a top-level master system.

7.1.6 Conclusion

A simple example has been provided so that the mechanics of fuzzy logic and Dempster-Shafer calculus can be applied, to motivate a general discussion of the merits of each and the challenges they present. The fuzzy logic system appears superior in speed, simplicity and flexibility. The Dempster-Shafer calculus appears superior in degree of automation and similarity to probability theory. Pure Dempster-Shafer is not at this time applicable for complex problem spaces in real-time systems. Various modifications and optimizations exist. So do hybridized versions of fuzzy logic, although their use is not likely to be mandated by real-time constraints.

7.2 Expert Systems and AI applications

7.2.1 Introduction

Expert Systems (ESs) constitute one of the most widely studied, deployed and tested areas in the set of techniques collectively called Artificial Intelligence (AI). An ES is intended to reproduce, within a relatively narrow area of knowledge (the expertise), the decision making behaviour of a human expert. As such it must be able to contain knowledge, make decisions based on knowledge and input facts, and explain its decision making process.

The latter three activities map quite directly on to the generally accepted architecture for a prototypical ES: a knowledge base, an inference engine, and an explanation subsystem. The separation of the declarative knowledge (knowledge base of rules and facts) from the control knowledge (the inference engine) clearly distinguishes an ES architecture from a standard computer program. In more common program architectures, control constructs such as "begin...end", "go to", "do...while", and so on, must perforce be intermingled with the domain knowledge that is being captured in the program's statements. In a typical ES, the domain knowledge is expressed as if-then rules and declared or input facts. These are rather easy for a person to maintain, as long as they remain relatively few (less than a couple of hundred). The control knowledge is all implicit in the operation of the inference engine subsystem; the ES programmer's view of this can be as simple as understanding the proper syntax, or at a more detailed level the order in which the parts of a rule are evaluated. A persistent ideal has been that the programmer need not have any view of the inference engine, as long as the expressed rules and facts are correct. This ideal has not been fully achieved in any systems deployed to date; the role of the "knowledge engineer" as ES programmers are known has not yet withered away to leave the domain expert alone with the workstation and ES environment.

The third point in the broad architecture of an ES is the explanation subsystem. This also is a requirement not generally imposed on standard computer programs. However, because an ES is meant to arrive at a human-like decision in a complex area, it is important to keep track of how it arrived at the decision. This is important both for debugging the knowledge base, and for gaining acceptance for the deployed system amongst its users -- if the system's line of reasoning is acceptable to the user then the decision, even if counterintuitive at first, is more likely to be accepted. Embedded ESs sometimes dispense with the interactive explanation facility, in favour of a trace logging system, or no explanation facility at all in the deployed ES.

Expert systems began as stand-alone, workstation-based products. Some even required custom hardware platforms. As the technology has become popularized, ES programming environments

(often called "shells") have appeared on popular PC, mini, and mainframe platforms. More important still has been the trend towards embedding ESs within larger systems, such as financial systems, library search systems, equipment analysis systems and so on. This has driven the technology in the direction of shells and toolkits more easily integrated with other computer programs written in a variety of high level languages.

7.2.2 Expert Systems and Real-time Constraints

While the concepts of EWCP are being proven in its first, perhaps partial software and hardware implementation, the system should not be overly constrained by development decisions based on real-time considerations. This is particularly true in the assessment of new algorithms and software technologies whose performance may be amenable to improvements of two or more orders of magnitude during a later optimization phase. This, however, does not mean that the real-time constraints of the problem domain should be ignored; in fact it is important to identify them early in the project, so that the results of the proof of concept phase can be evaluated intelligently. In addition, as much information as possible must be developed on the solution strategies used by advanced software algorithms and environments supporting the ES components. This is necessary in order to understand their limitations, and their amenability to performance optimization.

With this in mind, we can examine some of the important points relating to the Expert Systems and real-time.

An important note for EWCP is that most ES environments do not provide a means of specifying, imposing, conforming to, nor verifying conformance to real-time constraints. In addition, the commercially available toolkits (e.g. Nexpert) and shells (e.g. ART, KEE, GoldWorks, Humble) are not guaranteed to be "fast", compared to other software, once the rules are in place. Although "fast" and "real-time" do not have a direct relationship, enough of the one is often held up as a comfort or "risk reduction" factor for the other before the actual constraints are known. In practice there is no substitute for defining the real-time constraints early, so that the ES implementers can plan to meet them.

The real-time picture gets worse, however, as we consider another factor present in most ES environments: the garbage collector. As rules are evaluated (and objects manipulated in the object-oriented versions like Humble), memory space is consumed for new and temporary structures connected with the inference process. For example, if the antecedent of a rule is partially satisfied by a newly arrived fact, then some intermediate, partially-bound version of the consequent must be created and stored. If this path of reasoning ultimately fails, these data structures

become redundant and the space they occupy must be reclaimed, or garbage collected. This, on its own, is not a problem. The difficulty is that most systems provide no programmer control over the garbage collector: when it will become active, and how long it may take are effectively non-deterministic. This is the real-time programmer's anathema.

Fortunately, it is possible to construct ES engines which are stack-oriented so that garbage collection reduces to a pointer move (implying very high speed) during rule evaluation, and free-list insertion when programmer-mandated structure release (like fact erasure) takes place. The engines must be written in a compiled high level language like C or some versions of Prolog, or in Assembler. Particular attention must be paid to the memory management aspects of the engine.

Another option is to implement the ES directly in Prolog, or in a custom-developed language that can be converted by a C pre-processor into compilable C. (The recent releases of Prolog by some language vendors would very likely perform better than the latter choice). This approach has the advantage of eliminating the interpretation of rules by the engine altogether, potentially increasing speed by an order of magnitude or more. At the same time, it preserves the declarative aspect of the ES, and the consequent capability to handle very complex problems at a reasonable cost.

One successful military application of ES technology has been in the mission planning systems developed by Lockheed in the US. This, however, is a pre-mission, non-real-time application. The Pilot's Assistant project sponsored by DARPA was very ambitious and heavily funded, and has gone through major structural changes. The current structure of its ES components may offer some insight into what is feasible with today's technology, at least when a very large budget is available. However, the penchant in the US for starting with Lisp and gravitating back to C in ES development, may give a very skewed impression of what is really achievable with more modern tools and an early focus on defining and meeting real-time constraints. The typical development scenario shows very ambitious functional objectives being set at first because of the capabilities of the Lisp language, followed by disappointment in the projected temporal performance of the system, followed by a move to re-implement in C, followed by a budgetary limitation on what is achievable due to the poor function/cost ratio of C development, sometimes followed by the (re)discovery that algorithms have much more to do with speed in complex systems than does the choice of language.

Our conclusion about development environments then, is that a custom ES engine must likely be implemented to address the final product's real-time constraints. This naturally leads to a recommendation to do the implementation of the ES in a logic programming language such as Prolog

or a variant of Prolog, which brings the engine along with it. Structured languages are likely to be too expensive, and Lisp and Smalltalk contain non-deterministic garbage collectors. During the proof of concept phase, where speed is less of an issue, an Expert System Toolkit product in Prolog could be used to speed the development effort and focus it on domain problems rather than software engineering issues. There are a variety of such tools, some being in the public domain. The particular Prolog language implementation for the production system must be carefully chosen by surveying the memory management schemes used by the language implementor, as well as any control over memory management afforded by the implementation. The implementation chosen will very likely have to include a compiler rather than an interpreter only. Here again, the proof of concept phase need not be as constrained in its choice, although using the same language product that will eventually be used for the final product would be desirable for reasons of economy.

At all times, the language constructs used should be evaluated in terms of the likelihood that they are amenable to optimization after proof of concept. If an algorithm is inextricably bound to a language feature which may not be able to meet real-time constraints, the risk should be identified, evaluated and tracked. In Prolog, features to watch might be meta-programming, the use of non-indexed databases, and the use of any non-standard (e.g. object-oriented) features of the particular language implementation.

The adoption of the Prolog language approach raises a related issue: the use of heterogeneous (or "mixed") software languages to develop a set of modules which can be smoothly integrated. This is certainly an issue during the proof of concept phase, wherein the integration of a network of development workstations and disparate development, test and simulation tools will be essential. However, in a major modern software development, the issue must also be addressed in relation to the final product. Solving all the problems in one language or environment is likely to be too expensive; but the path to correct and high-performance integration of the disparate parts must be identified. While this document is not the forum to investigate the issue, it must be addressed before any software development begins, and is mentioned here because of its extreme importance to any machine intelligence modules. The AI component is sure to be prohibitively costly over its life cycle unless it can benefit from specialized language and development environment support.

7.2.3 Applications of Expert Systems in NEWCP

While advanced algorithms and software structures naturally suggest themselves in addressing the complex problems of NEWCP, the areas of likely application need to be investigated. In the first place, Expert Systems are only one of a large repertoire of such advanced technologies,

others of which may also be appropriate. In addition, the problem area must have some attributes of the kind of problems solved by experts. In particular there must exist (at least potentially) a set of rules, facts and heuristics which can be used to arrive at an adequate solution. In addition there should be some ambiguity and/or incompleteness in the solution space; otherwise, more standard software solutions are probably equally good candidates. On the other hand, care must be taken to distinguish between uncertainty management and ESs. An ES is not a prerequisite for consistent uncertainty management; such management can in fact be carried out in the complete absence of an ES.

The Tactical Situation Analysis (TSA) software can, in the light of these observations, definitely be assisted by Expert System technology combined with an uncertainty management system (UMS). The tactical situation can be analyzed by an EW operator or officer based upon incomplete, noisy and ambiguous information, and some useful decisions made. The expertise inherent in this should lend itself to an ES. In addition, the uncertainty associated with the evolving solution could well be managed consistently by the ES or its supporting inference engine. Challenges here are the definition of the rules, or domain knowledge, the capturing of it in an ES framework that is clear and easy to maintain, and the handling of the myriad of similar tactical situations without an explosion in the number of rules.

EW deployment decisions could also benefit from an ES, because of the expert knowledge they require, the constraints they operate under, and the short time frame allowed in which to make the decision. In this case, the explanation facility of the ES probably must be provided, so human experts can quickly review the reasoning behind deployment decisions for consistency, completeness and correctness. One key challenge is to implement such a facility that is capable of distilling the explanation into a very brief and clear form; only in such a form can the explanation be useful to human beings in stressful situations with sharp time constraints. The necessary abilities to handle focus of attention, generalization, and natural language are challenging. The decision making knowledge base and engine are of course challenging in their own right, but appear to be a good match for the strong points of ESs.

The effectiveness assessment process is another candidate for ES implementation, although it has a distinct requirement for procedural support as well. Given an ECM deployment with a known goal, this ES would invoke a procedure or function to generate expected threat responses perhaps associated with uncertainties, then monitor the incoming measurements to evaluate whether they match the expectations or not. Temporal and spatial logic are required by this ES, as are the ability to reason with default expectations and to undo controverted facts and inferences (non-monotonic logic). Some UMS is essential here, as is a careful attention to real-time constraints. In practice, the ES must also be capable of handling multiple deployments and making meta-

logical decisions regarding its own priorities and focus of attention.

All of the above-mentioned systems require the ability to communicate with one another. Effectiveness assessment, for example should not attempt to perform its task in complete ignorance of the evolving tactical situation and (especially) of deployment decisions. This communication could be at least partially handled by the proposed blackboard. However, management of the communication might itself be made the domain of another ES, perhaps only invoked when traffic becomes dense. This system might dynamically assign priorities to Blackboard event types, and even decide to abbreviate certain algorithms (by selecting a faster "canned" alternative) such as those in the UMS.

In summary, many of the EWCP processes seem to lend themselves to ES implementations, at least as part of the overall subsystem. In most of the cases, the ES might be the top level of the subsystem, supported by a variety of functional and procedural modules to perform time-critical work. In all cases, the implementation of the ES engine and of the knowledge base must be done with careful regard to efficiency, fast turnaround, deterministic worst-case behaviour, and reliability of memory conservation.

7.2.4 Conclusions:

We have introduced ES technology and examined some issues connected with it and its application to the EWCP problem domain. Since Expert Systems represent a relatively mature AI technology we have dealt with them in this separate section, and identified several areas of EWCP where they can prove worthwhile, and even essential.

We note however, that other AI technologies should not be ignored as the EWCP concepts are being proven. Amongst these areas are Neural Networks, Natural Language Processing, constraint logic programming, case-based reasoning, and qualitative physical knowledge.

We have examined the real-time issues associated with Expert Systems and recommended the development of the ES components in a logic programming language, Prolog or one of its variants. In so doing we have noted that the proof of concept phase need not be as strictly bound in its choice of tools which meet real-time requirements, since both algorithms and ES engines are amenable to significant optimizations. We have suggested the selection of a compiled Prolog implementation supplemented by third-party ES toolkit code in Prolog, for the proof of concept phase.

We have also raised the very important issue of integration of heterogeneous languages and tools

both at the proof of concept and the production phases.

8.0 Experiments, Simulation, and Analytical Tools

This section provides insight into experiments that could be performed, and software simulation packages, including analytical tools, that could be used to support testing of the various ECM effectiveness assessment algorithms comprising NEWCP. Also, a discussion pertaining strictly to the testing of expert systems is included.

In the most general case, effectiveness assessment for a target engagement will be based on combining evidence from a variety of atomic effectiveness assessment techniques. Atomic effectiveness assessment techniques include the measurement of jogs, trajectory deviations, chaff reflections, and radar mode transitions, and (possibly) apparent missile length change measurements.

Other aspects of the effectiveness assessment problem domain include the effects of the environment, individual sensor performance (e.g. accuracy, resolution, etc.), and the fact that the EW tactical picture is compiled based on data that originates in multiple sensors. In addition, it is envisaged that an uncertainty management system (e.g. Dempster-Shafer) will be employed to account for the uncertainty that originates due to limited sensor capabilities and the effects of the environment.

Because of the number of dimensions to the effectiveness assessment problem, experiments and simulation tests that will be performed in support of EW effectiveness testing should be performed in a logical progression. The general principle to be applied is that of "bottom-up" testing. More specifically, testing of atomic effectiveness assessment functionality is performed first. Once testing of atomic functions is complete, the atomic functions can be integrated together and tested as a whole (recall that effectiveness assessment is generally based on more than one atomic effectiveness assessment function).

Testing of the integrated system of atomic effectiveness assessment functions is itself not a single task. Instead, the complexity of the functionality under test becomes greater in discrete steps. For instance, testing of integrated atomic effectiveness assessment functionality is performed first with the assumption of no environmental effects and perfect sensor performance. In this case, we are simply testing the capability of the effectiveness assessment function to combine results from the execution of lower level effectiveness assessment functions. The effects of limited sensor capability are then added and the integrated system retested. Environmental effects are then added and the integrated system is retested, etc.

The following list of testing activities is intended to be representative of the recommended bottom-up approach to effectiveness assessment testing:

- Test each atomic effectiveness assessment function, based on measurements provided by a single sensor. Sensor performance assumed to be perfect; no environmental phenomena modeled;

- Test each atomic effectiveness assessment function, based on measurements provided by a single sensor. Sensor performance limitations (e.g. inaccuracy, blind zones) modeled. No environmental phenomena modeled;
- Test each atomic effectiveness assessment function, based on measurements provided by a single sensor. Sensor performance limitations (e.g. inaccuracy, blind zones) modeled. Environmental phenomena (e.g. multipath, precipitation) modeled;
- Test each atomic effectiveness assessment function, based on measurements provided by multiple sensors. Sensor performance limitations (e.g. inaccuracy, blind zones) modeled. Environmental phenomena (e.g. multipath, precipitation) modeled;
- Test integrated set of atomic effectiveness assessment functions, based on measurements provided by multiple sensors. Sensor performance assumed to be perfect. No environmental phenomena modeled;
- Test integrated set of atomic effectiveness assessment functions, based on measurements provided by multiple sensors. Sensor performance limitations (e.g. inaccuracy, blind zones) modeled. Environmental phenomena not modeled;
- Test integrated set of atomic effectiveness assessment functions, based on measurements provided by multiple sensors. Sensor performance limitations (e.g. inaccuracy, blind zones) modeled. Environmental phenomena (e.g. multipath, precipitation) modeled;
- Test integrated set of atomic effectiveness assessment functions, based on measurements provided by multiple sensors. Sensor performance limitations (e.g. inaccuracy, blind zones) modeled. Environmental phenomena (e.g. multipath, precipitation) modeled. Uncertainty management system introduced.

Another dimension to the problem domain not specifically represented in the above list is the number of threats and their complexity. If possible, the testing programme should proceed from testing effectiveness assessment performance for a single, simple threat to performance in a multi-threat environment where threats are more complex.

The general approach to effectiveness assessment testing provided above will require that special utilities be developed to support testing that is accomplished via simulation (as opposed to experimentation). Primary among these are "stubs" and "drivers". A stub is a functional entity that incorporates extremely simple functionality. For example, a stub for a sensor model might take true target position as input and provide that exact same data as output - this stub allows for simulation of a "perfect" sensor. A driver provides the necessary input to function under test. A driver generating true target positions could serve as a driver to a sensor model that then adds noise to these values in order to model sensor inaccuracy.

The category of experiments can be further divided into the following sub-classes: facilities, trials, and assets, while the category of simulation can be subdivided into evaluation packages and analytical tools.

8.1 Experiments

A variety of experiments can be performed to test the feasibility of the different ECM effectiveness assessment techniques proposed in this report, including the measurement of jogs, doppler changes, trajectory deviations, chaff reflections, IR profiles, and apparent missile length changes. In addition to testing the techniques themselves, environmental effects such as multipath, clutter, ducting, IR background, etc. must also be examined to gain insight into the circumstances under which these techniques will work reliably. For the sensor that will be used to execute the EA techniques, the following performance issues will be addressed: detectability profile for a given probability of false alarm rate and detection, angular resolution and accuracy, frequency resolution and accuracy, range resolution and accuracy, receiver sensitivity and dynamic range, measurement response/update time, antenna X-pol/co-pol isolation/purity, clutter rejection capability, multipath discrimination capability, etc.

There exist a variety of facilities and assets, available inside and outside of Canada, to support these experiments and are described below. Furthermore, a review of past sea trials, and those planned for the future, is provided to give an idea of some of the data that already exists, and will exist, which could support the evaluation of the various EA techniques.

8.1.1 Facilities

In Canada, there are a number of experimental facilities which could be used to support testing of the various aspects of EA techniques, falling under the categories of indoor and outdoor facilities.

Outdoor Facilities

i) Experimental Low Angle Tracking (ELAT) facility

The ELAT facility is located off the Ottawa river at Shirleys Bay, and is maintained by the Radar Division at DREO. The primary purpose of the site is to support low angle radar tracking experiments over water, to principally address the multipath problem. The facility comprises a trailer with a microwave receiver and data acquisition systems, and a vertical antenna array consisting of 8 dual polarized horns. ELAT can be used to test several issues relating to ECM effectiveness assessment, particularly i) propagation effects, and ii) jogs using the X-pol/co-pol, vertical array, and radar reflections techniques.

ii) Osborne Head

Osborne Head, located off the coast of Nova Scotia near Halifax, is a test site that could be used for evaluating NEWCP EA techniques in a naval environment. The site comprises 2 instrumented radars, the Sperry LN-127E navigation radar, and the SPG-515 CONSCAN tracking radar, and a TASS system. The navigation radar has been modified to allow the radar antenna to stare in one direction to simulate a tracking radar. It has also been provisioned to represent the effects of a CONSCAN system. The SPG-515 is a CONSCAN tracking radar with 3 scopes for the operator to locate and track the intended target. A trailer on site houses the navigation radar, as well as different data acquisition systems, such as digital recorders and video players, and test equipment. The site is ideal for conducting several tests for NEWCP EA algorithms, as well as characterizing the impact of environmental disturbances including multipath, clutter, etc.

iii) McMaster's propagation facility off Lake Huron

The communications research laboratory (CRL) of McMaster University developed a multi-parameter adaptive radar system (MARS) located on the west coast of the Bruce Peninsula overlooking Lake Huron. The MARS has a 32-element sampled aperture antenna that collects data at multiple frequencies. The facility can support similar experiments performed at the ELAT site described above.

Indoor Facilities

- i) Electronic warfare engagement simulation facility (EWESF)
- ii) PARAMAX testbed facility
- iii) DREV's testbed facility (IR)

i) EWESF

The electronic warfare engagement simulation facility (EWESF), situated at DREO and maintained by the radar countermeasures (RCM) section, is a real-time hybrid simulation laboratory comprising the following elements:

- an r.f. anechoic chamber,
- a hybrid threat radar simulator (TRS)
- a retrofitted MG-13 tracking radar
- a pair of antennas which move on a horizontal track to transmit simulated target/jamming signals, and
- a control room equipped with various computers and test equipment.

From the control room, the radars can be configured to represent specific threat systems, while targets and scenarios are programmed along with jamming waveforms. The jam signals may originate from an operational jammer or be implemented through simulation. The radar antenna

is located at one end of the chamber, receiving signals transmitted by the moveable antennas situated at the opposite end. The two antennas allow for the simulation of two targets dynamically displaced in angle (e.g. two ships, or one ship with decoy/chaff). The radars do not actually transmit in the chamber - they receive the target signal with a delay that is dictated by the simulated scenario or relative range between the threat radar and ship/decoy. The entire facility is tempest proof, allowing for testing up to the SECRET level.

The EWESF represents an excellent facility for testing various aspects of effectiveness assessment techniques. Typical scenarios and jam tactics can be simulated, and their subsequent effects on the threat radar be measured directly by NEWCP's EA algorithms, such as trajectory deviations, jogs, and radar mode changes, for real-time evaluation. The entire EWCP can be integrated into the EWESF to establish the baseline performance of the processor from effectiveness assessment to countermeasures deployment in a closed-loop manner.

ii) Paramax Testbed facility

The shielded testbed at PARAMAX combines simulators and stimulators along with actual equipment to test the ship sensors and the ship detection, tracking and TEWA software. Simulators are used to determine the actual signals which will be produced from targets (e.g. ASMs), and the stimulators are used to feed these signals to the surveillance radars, tracking radars, and ESM systems. The simulators / stimulators could be programmed to produce emissions and radar reflection signals associated with modern ASMs. The flexibility of this simulation / stimulation environment should allow the representation of the effects of a wide range of threat responses to countermeasures.

This facility could be used to perform test measurements, with the simulator programmed to produce the desired artificial signal. Because of the wide range of sensors represented at this facility, a wide range of effectiveness assessment techniques could conceivably be studied at this one facility.

iii) DREV's Testbed facility

The DREV testbed facility has been used to characterize the IR signature of a rocket motor. The testbed facility could be used to develop further IR profiles in order to determine the feasibility of using IR measurements as a means of effectiveness assessment.

DREV's IR capability includes the measurement of IR signatures of objects specifically in support of EW deployments. In addition, IR surveillance systems (e.g. AN-SAR(8)) and tracking systems (e.g. FLIR) can be studied and evaluated at the facility.

8.1.2 Assets

The following assets could be used to support experiments, falling under the general category of aircraft, ships, H/W simulators, H/W stimulators, and test equipment:

i) Aircraft

Helicopters or aircraft could be configured with on-board simulators and stimulators to replicate the RF emissions of a threat. The simulator could be programmed to produce the effect of a threat seeker jog. Such a signal could be used to stimulate an ESM system to measure the effectiveness of jog detection. By performing such experiments over water, multipath effects could be studied.

Aircraft flying carefully controlled trajectories itself could be used for the study of the feasibility of using doppler shift measurements in support of effectiveness. Similarly, such aircraft could fly profiles to support testing of effectiveness assessment techniques based on direct measurements of trajectory deviations. The following is a list of possible aircraft that could be used with corresponding systems:

- P3 aircraft with the Charlie and ALQ-170 (I/J band) pods
- AURORA with the APS-506 radar
- CT-133 (T-Bird) with the AST-501 stimulator pod
- EST Challenger with its various stimulators and receivers

ii) Ships

- CPF Sensor Suite

CPF sensors could be tested for their ability to perform jog detection, to measure doppler changes and trajectory deviations, to sense chaff reflections and IR emissions. The sensitivity and accuracy of the sensors to perform any of these measurements needs to be characterized. In addition, environmental effects (e.g. multipath, fog, etc.) on the performance of CPF sensors could be studied.

In order to evaluate the effectiveness assessment support provided CPF sensors, realistic target inputs to CPF sensors would need to be produced. This could be accomplished through the use of drone missiles or aircraft. Alternately, helicopter borne transmitters could mimic the RF emissions of threats, etc.

- Experimental ship used by the Radar division at DREO

iii) Hardware Simulators

Hardware (H/W) simulators, within the context of this report, refers to systems that both transmit and receive radar signals to achieve tracking. In some cases, where the simulator is implemented in an enclosed facility, the output power is diverted into a dummy load. The simulator comprises essentially the same functional modules found in the actual systems they represent with the exception the simulator is fully programmable to model a variety of systems or variances/modes of the same threat. The advantage of the simulator is that the effects of jamming can be evaluated. Stimulators, on the other hand, operate in transmit mode only, emanating radar-like signals as programmed. The following H/W simulators could be used to support EA tests;

ALQ-170 I/J Band Pods

The ALQ-170 simulators are contained in a pod which can be attached to an aircraft to support EW flight trials. They can also be integrated into a simulation facility, where key inputs and outputs to the pods are easily accessible. The '170 can operate in search mode, providing the operator with a PPI type scope display, or in track mode. Almost every aspect of the system is controlled by a computer so that radar parameters and operating modes are user defined through software changes, rather than through hardware. This makes the '170 extremely versatile and convenient for simulating a variety of threat systems or variances of a particular one. The advantage of the ALQ-170 with its pod mounted design, is that it allows for testing of NEWCP in a realistic naval environment.

The ALQ-170 I/J band pods are developed by Locus and maintained by NRL, U.S.

Charlie Radar

The Charlie simulator is a pod mounted system which represents only the SS-N-xx missile. Like the ALQ-170, the CHARLIE can be integrated easily into a laboratory environment. It was developed by NRL.

TRS and MG-13 radars

The threat radar simulator (TRS) and MG-13 radars reside in DREO's EWESF as discussed above. Both systems do not actually transmit in the facility, however, they do receive and track simulated radar signals emanating from the target antennas located at the opposite end of the chamber.

The threat radar simulator (TRS) is a hybrid simulation developed by the radar countermeasures (RCM) section at DREO. It is a non-coherent 2-channel monopulse radar capable of simulating search and tracking radars. All operational parameters are programmable. The TRS is also capable of RF agility, and leading and trailing edge tracking. It contains both A and B scope displays. The MG-13 radar is an operational radar, once flown on the CF-101 Voodoos. Since it is a commercial product with essentially fixed design features, it is limited in its ability to represent different threat

systems. The MG-13 is a LORO radar with a 3 channel monopulse antenna. It features home on jam (HOJ) and frequency agility, among other things. The radar can be removed from the facility as a stand-alone unit for field trials. The MG-13 could be used to measure reflections off a variety of antennas, such as parabolic, flat plate, and cassegrain, and different radomes to help determine the viability of using antenna reflections to detect jogs. The radar is also good for assessing the NEWCP's response to radar mode changes, particularly when the radar enters into HOJ mode.

iv) Stimulators

As described above, stimulators only transmit representative radar signals, and do not receive. Consequently, these systems cannot be used to test the effectiveness of jamming. Nevertheless, they can be used to provide realistic emitter density upon which to test EA techniques. The following H/W stimulators are identified;

- TASS
- Ex CEL
- Programmable synthesizers

TASS

The Tactical Signal Simulator (TASS) is a modular based simulator capable of representing a simple radar to an environment of highly complex threats in a dense background of less sophisticated emitters. TASS is a product of CAL corporation. The system comprises four principal blocks:

- a scenario computer, which control the overall operation of the simulator,
- a signal environment generator, which creates the digital time-multiplexed pulse stream from the emitters,
- a signal generator subsystem, which produces the rf or digital/video signals, and
- an interface to convert the output signals to the format and power required by the user.

The scenario includes the following features:

- 128 pre-programmable players,
- 512 way-points,
- emitter mode changes for specific scenario events,
- simulation of flight profile,
- simulation of roll and pitch on the receiver,
- graphical display of a planned view of the tactical picture.

The signal generator is capable of representing a variety of radar transmit features, including PRI

stagger/jitter, RF agility, antenna scanning, pulse width, pulse density of 500000 pulses/s for each of the six RF bands or 5 million pulses for fixed frequency radars, frequency chirp, direction of arrival, and many more.

ExCEL

ExCEL is a highly modular workstation-based system capable of simulating sophisticated emitters and complex EW scenarios. ExCEL makes use of multiple windows and comprehensive graphics to provide an intuitive interface to the user. The system comprises;

- synthesized and/or digitally tuned oscillator frequency sources,
- full 0.5-18 GHz coverage, (MMW option available)
- dedicated pulse-doppler,
- CW, and selectable bandwidth noise source channels,
- frequency modulation on all bands,
- PRI stagger, agility, and jitter,
- pulse width agility, stagger, and jitter,
- amplitude and pulse width modulation
- eight or sixteen complex emitter capability, and
- full scan and antenna editing capability for all emitters.

ExCEL can process up to 5 million digital pulses per second, and up to 800,000 different pulses (1.5 Megapulses as option) per second per microwave channel. The scenario generator is capable of simulating a variety of platforms, with any number of emitters, assigned with distinct velocities, altitude, and climb/descend/turn rates. The stimulator is capable of simulating direction of arrival (DOA) for each platform, defined by paths and waypoints. The DOA option is for 4 DF ports and 1 reference port. ExCEL is also capable of millimetre wave up to a frequency of 40 GHz.

ExCEL is produced by EXCALIBER of Ottawa.

v) Test Equipment

Conventional equipment

Spectrum analyzer

A conventional spectrum analyzer could be used to characterize some of the environmental effects which may degrade the performance of the effectiveness assessment techniques under study. One such effect which should be examined is the doppler spreading created due to multipath. The doppler spreading needs to be characterized to determine the effect it will have on the accuracy of the doppler measurements.

IR detectors

Equipment to measure IR emissions could be used to characterize the profile of a target in terms of the dependence of emitted IR power on angle from which the object is viewed. This needs to be studied in order to determine the effectiveness of IR detectors to build up IR profiles, and their ability to detect changes in the IR emissions.

I/J-Band RCS measurement radar

DREO, in the radar countermeasures section (RCM), has developed an I/J band RCS measurement radar which could be useful for NEWCP testing. The radar is a digitally based systems with the following features:

Frequency: 8-16 GHz
Transmit Power: 20 W
Sensitivity: -110 dBm
HPBW: 3° @ 9.0 GHz
Noise Figure: 4 dB
PRF: 1-100 kHz
Range Tracking: Mean centroid
Angle Tracking: Manual (optical)
receiver Bandwidth: 1 MHz
Dynamic Range: 70 dB (log/linear)
Sampling Rate: 8 bit @ 20 MHz
Polarization: Dual linear

Under computer control, the radar can automatically sample at various frequencies at both polarizations. This makes it ideal for characterising antenna reflections at different frequencies and polarizations in support of jog detection. Future plans for the radar are to introduce a coherent capability, and a mechanism for accepting antenna steering commands from a separate angle tracking radar.

8.1.3 Trials

A number of past sea trials have been performed, specifically by NATO, which could support the evaluation of the various effectiveness assessment techniques. In particular, measurements taken during the WESTLANT, EASTLANT, and BALTANT trials could be directly applicable. Other international trials include MACE, RAMSES evaluation, and TTCP/NATO joint ventures. Detailed information concerning these trials is not presented here for reasons of classification.

8.2 Simulation

The purpose of this section is to identify software simulation packages that could be used to support the evaluation of EA algorithms, and in some cases, the overall operation of NEWCP. It is assumed that the final algorithms will be written in software code that is compatible with the simulation environment in which they will be tested.

There are two types of simulation packages: i) software code which simulates the tactical environment in which EWCP must operate for non-real time evaluation of EA algorithms, and ii) analytical tools to perform off-line examination of specific technical issues, such as pulse level analysis, control loop analysis, signal processing analysis, etc.

8.2.1 Evaluation

There exist many simulation evaluation packages within Canada and abroad which could be used to evaluate the different EA techniques proposed for NEWCP. The simulation will allow NEWCP and its EA algorithms to operate under realistic tactical conditions in non-real time. Some of the simulations packages include:

- a) TACSIT/ASMD (old and new versions)
- b) ECMES (electronic combat modelling and evaluation system) (software sciences, UK)
- c) DREV simulation tesbed
- d) AAWSIM
- e) SCSS
- f) Decoy model (Denmark)
- g) SEAROADS (NL)
- h) Simulation of total electronic warfare systems (STEWS) (NRL, USA) pg 107 ISTI

a) TACSIT/ASMD

TACSIT / ASMD is a hybrid software package which combines the hardkill-oriented simulation TACSIT developed by Thomson-CSF and the softkill-oriented simulation ASMD developed by DREO. Both programs are written in Fortran and run in VAX environments. The hybrid allows for the simulation of engagements between ASMs and one or more naval platforms equipped with sensors, hardkill and softkill weapons and command and control (specifically TEWA) elements. Simulated naval platforms can be configured to incorporate a variety of sensors, weapons, and TEWA elements including:

- Surveillance radars;
- Multi-function radar;
- IRST;
- ESM;
- Tracking radar;

- Surface to air missile;
- Naval gun;
- CIWS;
- Chaff;
- RGPO / AGPO
- Active Off-board jammers
- rubber ducks; and
- TEWA (including effectiveness assessment).

The MFR performs the multiple target tracking and illumination function of advanced radars. The model is extremely flexible in the configuration of the radar parameters to represent different functionality, from a single STIR to an advanced multi-channel radar.

The ship signature is represented by a multi-scatterer model, to produce a ship RCS which varies with aspect angle and threat aspect-crossing rate. The ship characterization includes amplitude, phase, polarization, attenuation, and multipath.

The threat trajectory is calculated by the ASMD component of the hybrid. After monopulse seeker is activated, the threat path is determined by the action of the derived error signal on the missile guidance and control loops. The seeker has search, acquisition, lock-on, track, and re-acquisition modes and mode transition protocols. ECCM features include velocity memory and velocity discrimination, to help against RGPO.

The TACSIT model provides ESM data for each track. It also represents the TEWA functionality. Each threat is ranked principally on its expected time to impact on its associated target. Available weapons and softkill techniques are assessed for their predicted effectiveness against a threat, accounting for spatial interference, and the most effective asset is activated against the most dangerous threat. Several different TEWA alternatives exist in the model. Coordinated Hardkill/Softkill reduces the use of hardkill resources if the softkill deployed has seduced the threat away from the ship.

The softkill assets available to ASMD include chaff, passive decoys, and active ECM. Deployment methods include trainable launch, launch plus parachute, or placement of the side. Chaff can be deployed in either Seduction and Distraction mode. The active ECM can be configured to produce RGPO. An angular displacement can also be added to the RGPO to produce AGPO.

The model uses trajectory deviation measurements to determine whether a softkill reaction has been effective. Softkill effectiveness is gauged based upon a change in the threat heading towards the softkill, and a change in the CPA of the threat to the ship to exceed a specified kill radius.

The Hybrid model performs multiple Monte-Carlo runs of a threat scenario and compiles statistics

on the outcome of the scenario. Individual runs can be examined in detail against time via printouts of specified variables or graphics plots of signal levels, trajectories, and radar cells, power levels and seeker range gates.

Using this model, other issues involved with EA techniques could also be explored, such as the time required to perform result assessment, and whether sufficient time remains to deploy hardkill after a softkill reaction proves unsuccessful. The model has also proved useful in demonstrating the reduction in hardkill expenditure when effectiveness assessment techniques are in place.

b) ECMES

The electronic combat modelling and evaluation system (ECMES) program is a computer based model which provides the means to simulate a modern electronic warfare naval engagement. It features a closed-loop simulation capability, in which missile guidance is based on seeker tracking information, and hence, can be influenced by ECM. The model can be configured to evaluate the effectiveness of specific ESM systems, ECM systems, ECCM circuits, and the tracking behaviour of specific missile seekers. The seekers can be of the radar or IR type. The program is an event based model where events include the interaction of these systems on a pulse by pulse basis. ECMES was developed by Data Sciences of the UK, and is designed to run on UNIX or VAX based workstations. The program is written in PASCAL.

ECMES was chosen as the principal simulation package for the RAMSES Integrated Support Station (RISS) project, of which Lockheed Canada is the prime contractor, under the direction of DMCS 4. The mandate of RISS is to support jam techniques development and validation for the RAMSES jammer against a variety of threats in a multiple threat environment. A major contract is currently underway to enhance ECMES, to better meet the requirements of RISS, which are discussed. This package represents a substantial EW simulation capability and is considered to be a strong candidate for evaluating individual EA techniques, as well as the overall performance of NEWCP. A summary of the model is provided below, while a detailed description can be found in supporting documents residing at Lockheed Canada.

ECMES allows the user to model the electromagnetic interaction between a large number of independent platforms which may move freely in three dimensions within the modelled area. It is completely modular so that a variety of configurations and scenarios can be simulated for comprehensive testing. The following electronic combat sensors, weapons, and EW systems can be programmed:

- a) Surveillance radar
- b) Single target tracking radar
- c) Multi-mode radar including coherent pulse doppler processing
- d) Background emitters
- e) ESM receiver
- f) ESM processor

- g) Active or semi-active radar seeker
- h) Infrared reticle seeker
- i) Missile launcher and missile flight control
- j) Noise or responsive jammer
- k) Close-in weapons system
- l) Gun model
- m) Decoy launcher (chaff, IR flares, and active decoys)
- n) C³I elements of threat evaluation and weapon assignment, and EW control processor

ECMES is an interactive program which allows both input and output to and from the user terminal. The program makes extensive use of windows, of which many can be simultaneously opened to display i) simulation run time, ii) overview plan showing all platforms in the theatre, iii) platform summary listing platform characteristics and equipment installation and status, and iv) syntax for defining the various platforms and their equipment. In addition to the window displays, ECMES provides reporting facilities for off-line analysis of simulation runs, including: i) configuration log, which describes the details of platform and equipment set-up, ii) pulse data log, which contains a record of every pulse transmitted and received by any system during the simulation, iii) significant event log, which contains a record of significant simulation events and their time of occurrence, such as start of simulation, platform moving outside of simulation area, and chaff cloud launch, and iv) MPEL log, which contains a record of every event for every subsystem held on the master pulse event list (MPEL).

c) AAWSIM

An advanced AAW simulator has been developed in support of the Defence Research Establishment Valcartier. The program is written in Smalltalk and runs on an HP9000 computer. There are further plans to integrate a TEWA expert system testbed into the AAW simulator.

The work for the AAW simulator evolved from a requirement to provide a simulation environment with the following attributes:

- o Mechanisms to flexibly configure experiments
- o Mechanisms to generate data for analysis
- o A structure that is intelligible to the user, with modelling based on a direct mapping between entities in the physical system under study and components of the model
- o A capability for the model to evolve as knowledge of the system under study improves.

The model was developed using artificial intelligence technology including Expert System techniques and object oriented programming. Object oriented programming languages provide a methodology for characterizing entities and their interactions, which coincide with the problem of representing objects in an AAW scenario and their interactions in terms of signal emissions. The use of AI is important as well since future TEWA developments are likely to employ AI techniques.

The AAW simulator currently models the performance of variety of CPF / TRUMP like sensors and weapons. Modeled sensors include a long range surveillance radar, a medium range surveillance radar, an ESM system, and tracking radars. New models, representing an IRST for example, can be easily added to the AAW simulator.

The AAW simulator incorporates EW systems and models the interaction of such systems with the threat. The highly modular design of the simulator will allow for the possible development and installation of sophisticated models of EW systems and threat seekers and navigation systems. These capabilities could support the development and testing of effectiveness assessment algorithms.

d) SCSS

The Ship Combat System Simulation was developed by the United States Navy in SIMSCRIPT and runs in a VAX environment. The current Canadian version of SCSS has been modified under the direction of DMCS 2 to represent the Above Water Weapons systems found on the CPF. The software has recently been used by DMCS 2 to predict the outcome of missile firing trials. The SCSS model of the CPF ship includes the following systems:

- Long range surveillance radar (Sea Giraffe);
- Medium range surveillance radar (SPS-49);
- Tracking radar (STIR);
- Surface to air missile (Sea Sparrow);
- Naval gun (50 mm); and
- CIWS (Phalanx).

Part of the improvements to the model included modifications to the Threat Evaluation and Tracking Algorithms to use the CPF TEWA algorithms developed by PARAMAX.

The model includes an accurate aerodynamic model of a Vertically Launched Missile, with the velocity characteristics matching the manufacturer specifications, and the flyout using proportional navigation based upon missile seeker feedback.

Preliminary design work has been done to specify the modifications necessary to simulate the EW assets available to the CPF. This design work included representing the ESM and ECM capabilities provided by RAMSES and CANEWS, as well as modifying the threat seeker model to respond to the ECM and to provide ECCM.

e) Decoy model (Denmark)

The decoy model was developed for the Danish Defence Research Establishment. It is written in Ada and runs in a VAX environment. The purpose of the model is to determine the optimum position of an off-board decoy against a threat missile locked-on to the ship. The decoy may be

active or passive. The model also determines the effectiveness of the decoy deployment.

The criteria used by the model for decoy deployment accounts for the field of view of the missile, the position of the decoy in the missile range gate, the CPA of the missile to the ship. The model has the capability to represent multiple ships. The output from the program also includes suggested evasive angular manoeuvres to reduce the ship signature.

[Source of information: RSG-11 Panel documentation]

f) SEAROADS

The SEAROADS model was developed to provide simulation, evaluation, analysis, and research on Air Defence Systems. It is written in Turbo Pascal to run on a PC. The model is used in evaluating, analyzing, and studying the overall performance of air defence systems on naval vessels.

The model simulates an engagement between a given ship configuration and an air threat from hostile missiles in various settings. The model enables comparison for different tactics, systems and configurations in relation to a single ship in the AAW role, such as alternative TEWA.

Input such as the effectiveness of weapons and radar performance characteristics is supplied by lower-level models developed by various national research groups, such as the radar model CARPET and the missile model WASP.

The survival level of the ship is the main measure of effectiveness for the scheduling rules or tactics used in the scenario. Other output information includes the number of engagements, the detection ranges, and the weapon or chaff expenditure.

[Source of information: RSG-11 Panel documentation].

g) STEWS

The simulation of total electronic warfare systems (STEWS) software package, developed by the Naval Research Laboratory (NRL), evaluates ESM systems in medium-to-large scale electromagnetic environments. STEWS comprises a variety of models that simulate generic receivers and scenarios and primarily operates at a signal level with provisions for pulse level detail if required. NRL is in the process of implementing the effects of multipath, based on a sea-state value, ellipsoidal and spherical earth models for long range calculations, atmospheric effects on propagation, etc.

STEWS is written in FORTRAN IV and runs on the VAX 11/750 computer.

8.2.2 Analytical Tools

The following commercially available analytical software packages could be used to help analyze various technical issues pertaining to effectiveness assessment;

- MATLAB and Toolboxes
- SIMULINK
- EREPS
- CARPET (computer aided radar performance evaluation tool)
- Object oriented base models which facilitate fast prototyping/inheritance and testing of Expert Systems, Fuzzy Logic, and Dempster-Shafer techniques (HUMBLE, PROLOG, Smalltalk, Visual C++, etc.)
- DynaEst
- DETPROB
- RGCALC
- SIGCLUT
- MG-13 simulation

i) MATLAB and Toolboxes

MATLAB is an interactive environment for numeric computation, specializing in matrices, and combining extensive toolboxes or libraries of specific functionalities. One of the key features of MATLAB is its powerful graphics capability, which can display 2-D and 3-D graphs of any matrix (vector or complex) quickly and easily. The toolboxes that are available are:

- i) Control System, which features modern and classical techniques, state-space and transfer function models, model reduction, etc.
- ii) Systems Identification, which features parametrics and non-parametrics modelling, spectral analysis, recursive and batch techniques, model validation and goodness fit, model based signal processing, etc.,
- iii) MMLE3 State-Space Identification, which features identification of state-space models, NASA's MMLE3 algorithm,
- iv) Signal Processing, which includes digital and analog filter design, spectrum analysis, convolution, correlation, and FFT analysis, 1-D and 2-D signal processing,
- v) Robust Control, which includes LOG/LTR optimal control synthesis, singular value based model reduction, spectral factorization and model building, etc.,
- vi) Spline, which features piecewise polynomials and B-splines, spline construction and manipulation, datafitting and smoothing, function differentiation, integration, and evaluation, and,

vii) Chemometrics, which includes calibration matrix development, multiple linear regression, principal component regression, etc.

MATLAB operates on a PC and can be obtained from MATH WORKS Inc. of Natick, MA, U.S.A.

ii) SIMULINK

SIMULINK is a dynamic system simulation software which is built on the MATLAB numeric computation system and toolboxes. It operates in the Windows environment, and consists of blocks of functionalities which can be moved and connected, via the mouse, to other blocks to create simulations of complete closed-loop systems. The results can be viewed during the simulation run, and parameters can be changed dynamically so that the analyst can observe trends developing early on and make changes or continue with the configuration as desired. SIMULINK operates on a PC and can be obtained from MATH WORKS Inc. of Natick, MA, U.S.A. The package is ideal for implementing and/or evaluating TSA functionalities which support effectiveness assessment. For example, the control loop toolbox with its Kalman filtering module, may be used to represent and evaluating the tracking processes within the TSA.

iii) EREPS

EREPS (engineers refractive effects prediction system) was developed by the naval Ocean Systems Center Tropospheric Branch, Ocean and Atmospheric Sciences Division, and contains 5 stand-alone programs for performing electromagnetic propagation analysis. The package allows you to accurately predict the performance of any radar, electronic warfare, and communication systems operating over water in the 100 MHz to 20 GHz frequency range. Propagation effects which are modelled include: refraction, evaporation and surface-based ducting, diffraction, tropospheric scatter, and water vapour absorption. The package runs on a PC and can be obtained by Artech House Publications of Boston. The EREPS package is ideal for gaining insight into how environmental effects may impact the performance of specific sensors, where uncertainties can arise in measurement and detection.

iv) CARPET

The computer-aided radar performance evaluation tool (CARPET) is used for the assessment and design of surface based (maritime and land-based) radars. It considers the entire radar system and its environment, including: transmitter/receiver characteristics, clutter, jamming, and propagation phenomena. It assesses the effects of radar parameters and environmental conditions on detection probability as a function of range, velocity, or height.

CARPET runs on a PC and can be obtained from TNO Physics and Electronics laboratory.

v) DynaEst

DynaEst is an interactive design tool for Kalman filters and an adaptive multiple model estimator. Statistical tests of the Kalman filters may be performed, including the normalized estimation error squared (NEES), the normalized innovation squared (NIS), and the RMS errors. The package provides an effective tool in dealing with practical problems of estimation and tracking, which are relevant to measurements of trajectory deviations, and doppler shifts.

DynaEst is a software package that runs on a PC and is made available through Artech House Publications of Boston.

vi) DETPROB

DETPROB tabulates the probability of detection of various types of radar targets for a wide variety of conditions. It operates on a PC and is available from Artech house Publications of Boston.

vii) RGCALC

RGCALC predicts radar detection performance for a variety of radar parameters and environmental conditions. It can be obtained from Artech House Publications of Boston.

viii) SIGCLUT

SIGCLUT calculates and plots the received signal-to-noise ratios for nearly any type of beam target, including point targets and jammers, distributed surface clutter and volumetric clutter (rain or chaff). The package runs on a PC and can be obtained from Artech House Publications of Boston.

ix) MG-13 Simulation

A detailed simulation of the MG-13's antenna, azimuth and elevation servos, and AGC was developed at Lockheed Canada in support of X-eye and X-pol research. The program deals with co-pol and cross-pol electric fields to determine the radar's response to various forms of X-eye and X-pol jamming strategies. Different sweep rates and limits can be programmed to gain insight into the specific patterns of jogs that may occur with a typical LORO antenna. This in turn can be applied to the NEWCP's jog detection algorithms for detailed analysis.

8.3 Expert System Testing

This section reviews methods and tools suitable for assessing expert systems (ES). As discussed in section 7, an expert system is a computer program that attempts to reach a decision similar to what a human expert would make given the same set of inputs and circumstances. The principal

elements of an ES is the knowledge base (KB), inferencing engine, and explanation utility. The ES, within NEWCP, supports the EA module of NEWCP in the following areas: missile detection, jog detection, radar mode change, trajectory deviation, chaff cloud reflections, and missile kill. The test of the ES is to ensure these EA functions are performed in an effective and efficient manner.

The three categories of tests are validation, verification, and evaluation. Evaluation is more encompassing, dealing with the expert system's overall worth in terms of cost, efficiency, maintainability, etc. This section addresses primarily validation and verification.

8.3.1 Verification

In simple terms, verification checks to make sure the ES/KB has been coded correctly, while validation ensures that the code in the ES/KB is correct. Verification, which can be performed manually or with automated tools, scans the rule base within NEWCP to report on:

- goals and subgoals that are not reachable
- rules that can never fire
- data values never used (variable clause check)
- conflicting rules
- circular rules
- variable-unsafe clause checking
- flow analysis

Few tools manage to achieve very strong capabilities in detecting semantic (logical) errors connected with variables rather than data values (cf: data values never used). One form of such checking, to capture the common error of misspelling a local variable, resulting in failed pattern matching within a rule, is called variable-unsafe clause checking. Since rule firings intrinsically depend on pattern matching, this is a very important tool. If systems can pass variable values unbound, another important tool is flow analysis, which checks whether and where unbound variables can ever obtain values.

The manual approach requires that the user methodically stimulate each decision branch of the ES to ensure the above deficiencies do not exist. This could be time consuming, given the permutations that can exist regarding: i) threat scenarios and responses, ii) potential number of uncertainties and uncertainty types at each stage of NEWCP, and iii) the amount of information residing in the knowledge base. To minimize the overhead in verifying the ES all at once, the process could take place at each stage of development of the ES, using an object oriented language such as Smalltalk or C++, which are ideal for prototyping. Once the software code is deemed acceptable, it can be compiled into an embedded real-time system using C or assembler language.

Many commercial development environments contain some tools for validating the expert system

rules they help to generate. These include expert system shells such as HUMBLE and VPEXpert, and language compilers such as Prolog and LISP, as discussed in section 7 of this report. These are better developed at the syntactical than the semantic level, though systems typically contain at least some tools from our list. Automated checking of systems which were not developed within a special development environment is not yet very advanced. Even CASE tools oriented to analyzing C (e.g. TeamWork) and Ada code (e.g. Rational Rose), for example, do not achieve the level of support for semantic content that is required to maintain an expert system. They also tend to carry a very high price tag. Some research in these areas has been carried out by Lockheed (USA), and is worth investigating.

Another matter worth noting in this regard is that much work has been done on the correct generation of logical programs in the Prolog paradigm. Methodologies exist which can guarantee that programs generated are complete and correct, and that can also search the solution space for the most efficient of such implementations [Dewille, Y. (1990), Logic Programming, Systematic Program Development, Addison-Wesley, N.Y.].

8.3.2 Validation

Validation is concerned with the accuracy, completeness, and consistency of the ES. Accuracy defines how correct the ES was in performing EA. For example, did a jog event occur, or did the signal fade as a result of multipath. The ES would have to deal with this potential ambiguity by looking at a number of parameters, including the rate and depth of the jog fade, the sea state, height and range of the missile, etc.

Validation testing can be supported by various tools, depending upon their availability for the software languages used, and upon the amenability of those languages to semantic analysis. In the final analysis, the test team must thoroughly understand both the tools and the test methodologies, and proceed with the various accepted levels of testing. One can test individual function/ procedure calls, major modules, complete subsystems, and the fully integrated system. Along a different taxonomy, one can test for correctness, completeness, conformance to real-time constraints, determinism, availability, computer memory management integrity (which impacts availability), and fault-tolerance. This rather daunting list is incomplete. In short, the testing problem is too great in practice to solve on a finite budget. However, it is customary to put in place a defined system of testing (e.g. according to MIL standards) and comply with its requirements, as a minimal safeguard for system quality. Typically this test system will involve tests at the function, module and subsystem granularity (cf: rule, rule-base, EWCP in our problem domain) followed by feedback from system integration testing. Also typically, some custom functions or "test harnesses" will have to be written. For economy, these harnesses should use as much of the subsystem and system code as possible, supplemented by a small amount of input/output code to feed test cases to the software under test. Various degrees of support for this activity are available in development toolkits and free-standing test products, as discussed in section 7 of this report. Not many of the latter have appeared in the Expert System arena, as most are currently just maturing for C, Cobol, Fortran, and Ada. Languages like Smalltalk and

Prolog allow function and module testing directly within the development environment. Section 7 provides a more detailed description of the appropriate expert system development environments which support testing. PDC Prolog (written by the prolog development center of Copenhagen) even supports direct saving of the test inputs and results together, through a few keystrokes; in this way the developer's feedback becomes the low-level testing paper-trail. Such testing is virtually cost-free, although some auditing of the output from the programmers is necessary to ensure that the desired cases have been covered.

Subsystem level testing (e.g. major parts of EWCP, and EWCP itself as viewed from the system perspective), cannot generally be addressed in this way. They usually require software test harnesses to be written, or third-party tools to be configured, to stimulate the software under test with data, and to gather the relevant outputs (and intermediate, internal values). Whether supported by tools or not, these tests must be designed to permit the decision on validation to be made. This in turn implies that taxonomies other than module granularity must be superimposed on the test plan, the appropriate tests designed and the relevant data collected.

Because uncertainty and randomness are features of the EWCP problem domain, and because knowledge bases can be more or less sensitive to these factors, multiple tests with the input stimulus varying over and beyond the expected ranges are justified. This can help to elucidate failure modes at the subsystem level, and to characterize the correctness and accuracy of the system's outputs, whether they be in the form of single decisions or ordered lists of possible decisions.

A survey of test environments that may support these activities is necessary in the beginning of the proof-of-concept implementation phase. Whether or not a tool is chosen, a coherent test plan and methodology will also have to be written, and the necessary accommodations made to ensure that it can be implemented within the software development environment chosen for the development team. This comprises the accommodation of functional requirements of the tools and methods, as well as the more mundane but unforgiving matters of network and software compatibility.

8.3.3 Conclusions

For ES development, practical considerations (e.g. the availability of the more specialized list of tools) dictate that testing is inextricably linked to the development environment. A driving consideration must be that rule-based systems are too expensive to develop and test in imperative languages such as C and Pascal without specialized development tools that support the declarative nature of rules. At the sub-system and system level, the distinction between the testing of rule-base and procedural software systems effectively disappears.

Annex A

This annex presents the equations to calculate typical co-polar/crosspolar antenna responses of a paraboloidal reflector antenna. Refer to figure A-1 for a definition of angles.

$$E = \frac{+j\omega\mu}{2\pi Z_0} \int_0^{\psi/2\pi} \int_0^{\psi} \frac{|E| \cos(\frac{\psi}{2}) E_r}{\rho'_{ABCD}} \left[\frac{\rho^2}{2F} \sqrt{\rho^2 \sin^2 \psi + 4F^2} \cos \psi \sin \psi e^{-j \frac{2\pi}{\lambda} [d + \rho'_{ABCD}]} d\phi d\psi \right]$$

$$e_{iy} = \cos(\eta - \eta')$$

$$E_r = \frac{\cos \beta}{M} [-\sin \psi \cos \phi \sin A e_{rx} + (\cos \psi \cos A + \sin \psi \sin \phi \sin A) e_{ry} + \sin \psi \cos \phi \cos A e_{rz}]$$

where

$$\beta = \tan^{-1} \left[\frac{\sin \psi \cos \phi}{\cos \psi} \right]$$

$$M = \sqrt{(\sin \psi \cos \phi \sin A)^2 + (\cos \psi \cos A + \sin \psi \sin \phi \sin A)^2 + (\sin \psi \cos \phi \cos A)^2}$$

$$A = \tan^{-1} \left[\frac{\sin \psi \sin \phi}{\cos \psi} \right]$$

$$e_r = \begin{bmatrix} e_{rx} \\ e_{ry} \\ e_{rz} \end{bmatrix} = \begin{bmatrix} 2n_x^2 - 1 & 2n_x n_y & 2n_x n_z \\ 2n_x n_y & 2n_y^2 - 1 & 2n_y n_z \\ 2n_x n_z & 2n_y n_z & 2n_z^2 - 1 \end{bmatrix} \begin{bmatrix} e_{ix} \\ e_{iy} \\ e_{iz} \end{bmatrix}$$

and the unit normal to the reflector surface is given by:

$$\hat{n} = n_x \hat{x} + n_y \hat{y} + n_z \hat{z}$$

$$n_x = \frac{-\sin\psi\sin\phi}{\sqrt{\sin^2\psi + \frac{4F^2}{\rho^2}}}$$

$$n_y = \frac{-\sin\psi\cos\phi}{\sqrt{\sin^2\psi + \frac{4F^2}{\rho^2}}}$$

$$n_z = \frac{2F}{\rho\sqrt{\sin^2\psi + \frac{4F^2}{\rho^2}}}$$

For the COPOLAR response, use:

$$e_{ix} = -\sin(\eta - \eta') \sin(\theta - \theta')$$

$$e_{iy} = \cos(n - n')$$

$$e_{iz} = -\sin(\eta - \eta') \cos(\theta - \theta')$$

For the CROSSPOLAR response, use:

$$e_{ix} = \cos(\theta - \theta')$$

$$e_{iy} = -\sin(\theta - \theta') \sin(\eta - \eta')$$

$$e_{iz} = -\sin(\theta - \theta') \cos(\eta - \eta')$$

and also,

$$d = \sqrt{(x_r - x_{fp})^2 + (y_r - y_{fp})^2 + (z_r - z_{fp})^2}$$

where,

$$x_r = F \sin \theta + \rho \sin \psi \sin \phi \cos \theta - \rho \cos \psi \sin \theta$$

$$y_r = F \cos \theta \sin \eta - \rho \sin \psi \sin \phi \sin \theta \sin \eta + \rho \sin \psi \cos \phi \cos \eta - \rho \cos \psi \cos \theta \cos \eta$$

$$z_r = F \cos \theta \cos \eta - \rho \sin \psi \sin \phi \sin \theta \cos \eta - \rho \sin \psi \cos \phi \sin \eta - \rho \cos \psi \cos \theta \cos \eta$$

$$x_{fp} = R \sin \theta$$

$$y_{fp} = R \cos \theta \sin \eta$$

$$z_{fp} = R \cos \theta \cos \eta$$

$$\rho'_{ABCD} = \sqrt{(x_f - \rho \sin \psi \sin \phi)^2 + (y_f - \rho \sin \psi \cos \phi)^2 + (-\rho \cos \psi)^2}$$

where, for each of the feed horns:

$$A \rightarrow (x_f, y_f, z_f) = (+\Delta x, +\Delta y, F)$$

$$B \rightarrow (x_f, y_f, z_f) = (+\Delta x, -\Delta y, F)$$

$$C \rightarrow (x_f, y_f, z_f) = (-\Delta x, +\Delta y, F)$$

$$D \rightarrow (x_f, y_f, z_f) = (-\Delta x, -\Delta y, F)$$

$$\rho = \frac{2F}{(1 + \cos \psi)}$$

and finally, the expression for Ψ is:

$$\Psi' = \tan^{-1} \left[\frac{D/2}{F - D^2/16F} \right] = \tan^{-1} \left[\frac{D}{2F - D^2/8F} \right] = \tan^{-1} \left[\frac{8DF}{16F^2 - D^2} \right]$$

Geometry for front-fed parabolic reflector monopulse antenna model

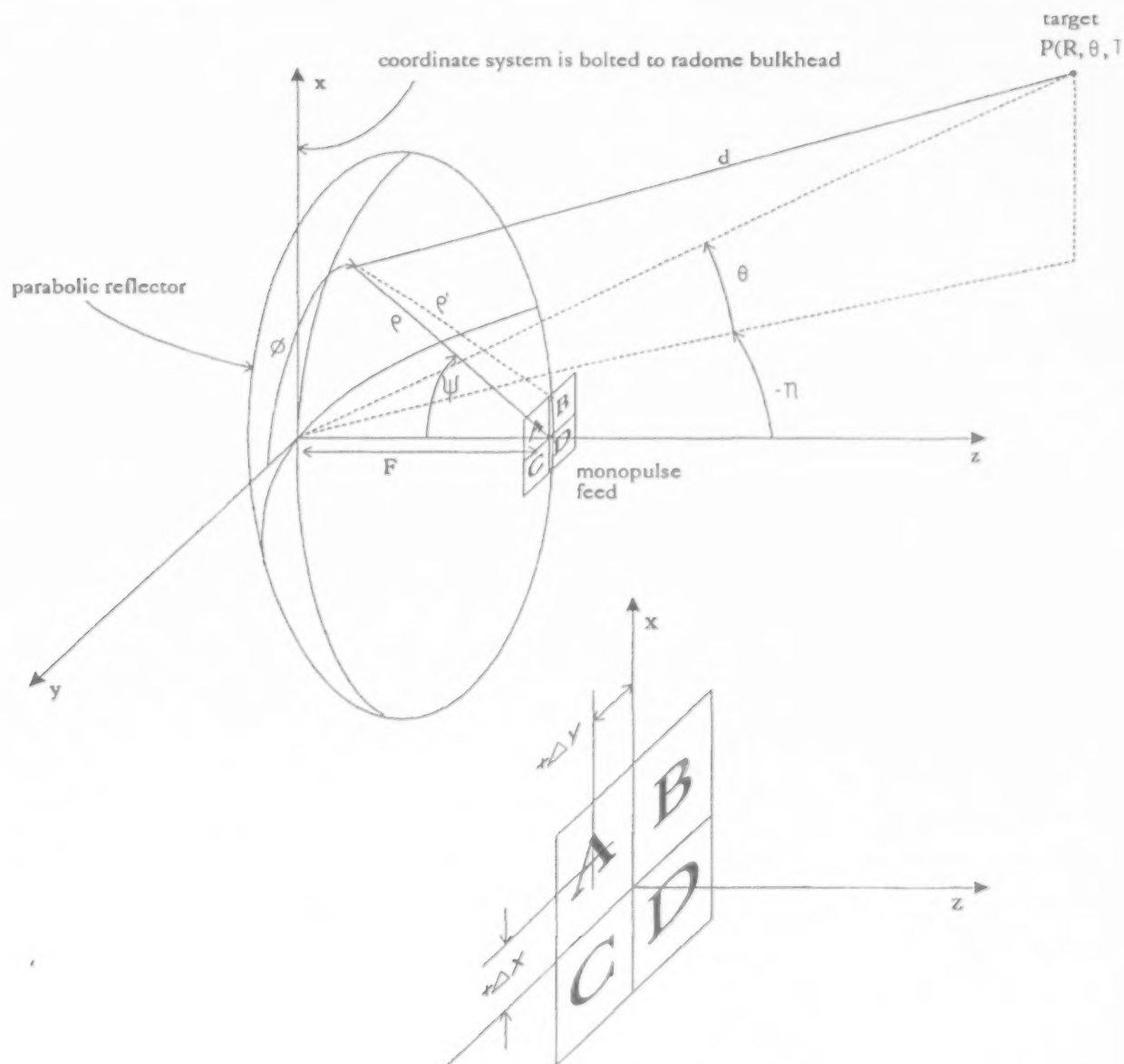


Figure A-1 Geometry for front-fed parabolic reflector monopulse antenna model

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